

Transitioning to Quantum-Safe Cryptography on IBM Z

Bill White

Didier Andre

Gregg Arquero

Ritu Bajaj

Joe Cronin

Anne Dames

Henrik Lyksborg

Alexandra Miranda

Maxwell Weiss



Security

IBM Z



IBM Redbooks

Transitioning to Quantum-Safe Cryptography on IBM Z

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Note: Before using this information and the product it supports, read the information in “Notices” on page vii.

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This edition applies to the quantum-safe capabilities available with the IBM z16 and IBM z15.

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Preface

As cyberattacks continue to increase, the cost and reputation impacts of data breaches remain a top concern across all enterprises. Even if sensitive data is encrypted and is of no use now, cybercriminals are harvesting that data because they might gain access to a quantum computer that can break classical cryptographic algorithms sometime in the future. Therefore, organizations must start protecting their sensitive data today by using quantum-safe cryptography.

This IBM® Redbooks® publication reviews some potential threats to classical cryptography by way of quantum computers and how to make best use of today's quantum-safe capabilities on the IBM Z platform. This book also provides guidance about how to get started on a quantum-safe journey and step-by-step examples for deploying IBM Z® quantum-safe capabilities.

This publication is intended for IT managers, IT architects, system programmers, security administrators, and anyone who needs to plan for, deploy, and manage quantum-safe cryptography on the IBM Z platform. The reader is expected to have a basic understanding of IBM Z security concepts.

Authors

This book was produced by a team of specialists from around the world working remotely for IBM Redbooks, Poughkeepsie Center.

Bill White is an IBM Redbooks Project Leader and Senior IT Infrastructure Specialist at IBM Poughkeepsie, New York.

Didier Andre is a Senior Technical Specialist with expertise in IBM Z Security, working for the IBM Washington Systems Center. He joined IBM in 2001, in France, as an experienced system programmer supporting multiple clients before moving to the US in 2015 where he worked for IBM Systems Lab Services as a security expert, leading the security team over 6 years.

Gregg Arquero is a Senior Software Engineer at IBM. He joined IBM in 2015 working with the IBM z/OS® ICSF team. During his time on the ICSF team, he designed and developed several key crypto solutions on IBM Z, such as early ICSF availability at IPL, AES-DUKPT support, and quantum-safe algorithm support. He is also an avid innovator with over a dozen granted patents by the USPTO. He received his bachelor's degree in Computer Science from Binghamton University.

Ritu Bajaj is a Senior Design Researcher at IBM Z. As an empathetic designer and business professional, she uses human-centered design and user experience (UX) research to create value-add strategies for product innovation and sustainable business growth. She joined IBM in 2020 and collaborated with the IBM Z Security Hardware teams. She led the sponsor user program and client engagements for quantum-safe cryptography to gather feedback and synthesize clients' insights for starting IBM z16™ and enhancing ADDI with cryptographic discovery. She conducted UX heuristic evaluations for the Fully Homomorphic Encryption (FHE) toolkit and the IBM Z Security and Compliance Center dashboard. With dual degrees in M.Design from Illinois Institute of Technology and an executive MBA from Michigan State University, she applies her diverse knowledge in strategic and design thinking methodologies to solve customers' problems and explore use cases.

Joe Cronin is the North American lead Cybersecurity SME for IBM Systems Lab Services. He has been a systems programmer and engineer, presenter, and educator for over 40 years. His concentration has been in security architecture, governance, compliance, audit, identity management, and design. He has a broad depth of knowledge across z/OS® and distributed systems.

Anne Dames is a Distinguished Engineer in the IBM Z Cryptographic Technology area. She received a B.S. degree in Mathematics from Johnson C. Smith and a M.S. degree in Computer Science from the University of North Carolina at Charlotte. She has held various positions in firmware development, software, and product engineering. She has years of experience as a development leader for the IBM Hardware Security Module product line and the IBM Common Cryptographic Architecture (CCA). She is currently leading a cross platform development effort to use quantum-safe cryptography.

Henrik Lyksborg is a Senior IT Specialist working in the IBM Crypto Competence Center based in Copenhagen, Denmark. He is a product owner for cryptographic appliances and APIs, such as IBM Enterprise Key Management Foundation (EKMF), IBM Advanced Cryptographic Service Provider (ACSP), and IBM Crypto Analytics Tool (CAT). Henrik studied Electrical Engineering at the Technical University of Denmark. He joined IBM in 1991 with a B.Sc. in Electrical Engineering and worked with IBM mainframe software licensing and client software maintenance delivery processes. In 2017, he took on an IBM internet payment platform job, dealing with Payment Card Industry (PCI) controlled business applications. Currently, Henrik works with cryptographic key management, cryptographic services, and cryptographic compliance controls to ensure that keys, certificates, and cryptographic material are well managed and documented.

Alexandra Miranda is a z/OS System SSL function and system tester and developer, and a z/OS Content Designer. She has been working at IBM since 2018, after graduating with a BS in Computer Science and a BA in Creative Writing and Mathematics.

Maxwell Weiss is a Technical Specialist supporting the IBM Z Security portfolio for Worldwide technical sales. One of his areas of focus includes supporting customer adoption of IBM Hyper Protect Data Controller and IBM Enterprise Key Management Foundation Web Edition (EKMF Web) for pervasive encryption key management. Before this role, Max was a Technology Architect in the IBM Client Engineering for Systems, supporting pre-sales activities for the IBM Z stack.

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Cryptography in the quantum computing era

For decades, organizations used cryptographic algorithms to protect their most sensitive data and communications in computer systems, networks, and storage devices. Imagine if an adversary or cybercriminal can break those cryptographic algorithms that you relied on for many years. What are the potential impacts on your business?

Once considered impossible, attacks that can compromise today's cryptographic algorithms can become possible with a powerful quantum computer. Your protected data can be stolen, exposed, altered, disabled, or destroyed through new attack vectors that increased in the quantum computing era.

Although quantum computers are still in their early stages of adoption, their use soon will be more widespread. A single quantum computer can be capable of performing millions of computations simultaneously.

Because quantum computers deal with probabilities, the problems they are good at solving are exponential in nature. That is, today's cryptographic algorithms might be threatened by quantum computers, potentially exposing sensitive data.

Attackers are already harvesting protected data in anticipation of cracking the protection algorithms sometime in the future. Therefore, it is important to take action now: assess the cryptography methods that are used today to protect your data, applications, and systems; understand the vulnerabilities in the quantum computing era; and evaluate the quantum-safe capabilities that are offered with the IBM Z platform.

This chapter includes the following topics:

- ▶ 1.1, "When will quantum computers break cryptography" on page 2
- ▶ 1.2, "Why are quantum computers a threat" on page 4
- ▶ 1.3, "Impact of Shor's and Grover's algorithms" on page 7
- ▶ 1.4, "Cryptographic vulnerabilities possible with quantum computers" on page 9
- ▶ 1.5, "New algorithms to counter CRQC attacks" on page 11
- ▶ 1.6, "Quantum-safe capabilities with IBM Z" on page 13

1.1 When will quantum computers break cryptography

The question of when quantum computers might break cryptography is often asked, but unfortunately presents the threat as being in the future. Consider the following point from the World Economic Forum, which was held in May 2021^[1]:

For data that will require protection for decades, the threat is today. The impact is in the future.

Many IT decision-makers plan to retain their data 11+ years into the quantum era as per the IBM MD&I survey². Their data includes personal identifiable information (PII), trade secrets, intellectual property, and other sensitive digital assets. This information already is at risk because they need to store it and keep it confidential for decades.

Although cybercriminals cannot easily break most encrypted data today, they might be able to decrypt that data in the future by using a large quantum computer, also known as a *cryptographically relevant quantum computer* (CRQC)³. Because it is unknown when YQK⁴ will happen, it is best to start looking at ways to protect your data now:

*Act now—it will be less expensive, less disruptive, and less likely to have mistakes caused by rushing and scrambling.*⁵

1.1.1 Business risks

The cost of data breaches continues to increase, with strong encryption being the top mitigating cost factor. The global average total cost of a data breach is \$4.24 million per the [Ponemon Cost of a Data Breach 2021 Study](#).

Organizations that use strong encryption (such as AES with 256-bit keys) for data at-rest and in-flight, had an average total cost of a breach of \$3.62 million, compared to \$4.87 million for organizations that use weak or no encryption, which results in a difference of \$1.25 million or 29.4%.

Most businesses expressed shared concerns for data, system integrity, and software verification at risk with the potential threats of CRQC attacks. They recognized CRQC attacks as a cybersecurity⁶ risk. However, organizations are just beginning the cryptographic inventory⁷ phase of a quantum-safe journey.

Additionally, many organizations operate within highly regulated industries and must comply with standards. The National Institute of Standards and Technology (NIST) has a post-quantum cryptography standardization process to identify algorithms that are resistant to attacks that might be started from quantum and conventional computers. BSI, a German federal agency, requires the use of hybrid schemes in which both classical and quantum-safe algorithms are used for protection in high-security applications.

¹ Reference [Is your cybersecurity ready to take the quantum leap? \(2021\)](#)

² An IBM Marketing study

³ CRQC is used to specifically describe quantum computers that are capable of breaking cryptographic algorithms used on conventional computers.

⁴ YQK is a colloquial term, in reference to Y2K, used by Dario Gil, IBM SVP and Director of Research to describe the point at which quantum computers could be powerful enough to brute force their way through today's encryption. (The Hill: [YQK is coming — time to get 'quantum-safe'](#))

⁵ Reference [NIST PQC Standardization Update-Round 2 and Beyond \(2020\)](#)

⁶ Cybersecurity is the practice of defending computers, servers, mobile devices, electronic systems, networks, and data from malicious attacks.

⁷ Cryptographic inventory is a strategic cybersecurity asset. It enables an organization to enforce a secure cryptographic policy across IT infrastructure and react quickly to security issues; efficiently carry out strategic transformations, such as migrating cryptography services to the cloud or deploying post-quantum cryptography.

The post-quantum cryptography standards and work groups are to be the business driver for security policy changes and crypto migration planning.

IT executives can proactively mitigate the risk of business disruptions that are caused by CRQC attacks. Currently, some organizations decentralized small-size crypto groups that are scattered across the IT business units, which causes disconnection and inertia against cryptographic agility⁸. Many IT organizations still do not have a comprehensive view of the cryptography in use in their institution because they lack cryptographic inventory tools and skills for the broad cryptography landscape.

A few cryptographic services groups implemented proprietary crypto libraries and abstraction layers that simplified managing the crypto updates and prepared them for cryptographic agility. Businesses, such as banks, expressed concerns about the effect of quantum-safe algorithms on system performance and latency.

Organizations, such as automobile manufacturers, must deal with programming resource constraints, such as key length size and RAM, to accommodate the use of public key quantum-safe algorithms and schemes in their new application development process.

Organizations also are interested in quantum-safe encryption to protect their long-lasting sensitive data and future-proof it. Quantum-safe readiness is on most organizations' roadmap. Some already benchmarked quantum-safe algorithms and explored cryptographic inventory tools for application modernization.

1.1.2 Quantum threats and implications on data and identity

What will a cybercriminal be able to do with a quantum computer? Why do organizations need to act now? Why is the data at risk⁹ today?

A cybercriminal who uses a powerful quantum computer to break the current cryptography features the following threats¹⁰ and implications:

- Passive attacks on confidentiality

Cybercriminals might harvest data communications, recover session keys from encrypted channel negotiation, and decrypt communication transmissions. They can steal snapshots of encrypted cloud data, extract keys that are protected by using public keys, and conduct retrospective decryption.

Cybercriminals might decrypt lost or harvest historical data through cracking encryption keys. An organization's sensitive data that is protected by using today's cryptography might be vulnerable in the future. Encrypted data that is stolen during a data breach and encrypted media that is improperly disposed or stolen are both at risk.

- Impersonation attacks on identities

Cybercriminals might create fraudulent code updates, insert malware, change configuration settings, and create damage. They might transfer assets on a blockchain or manipulate updates and forge transactions through fraudulent authentication. With quantum threats, identity over the internet and software authenticity cannot be guaranteed.

⁸ Cryptographic agility is about an information security system rapidly switching to alternative cryptographic primitives and algorithms without making significant changes to the system's infrastructure.

⁹ A measure of the extent to which an entity is threatened by a potential circumstance or event, and typically a function of the adverse impacts that can arise if the circumstance or event occurs; and the likelihood of occurrence.

¹⁰ Any circumstance or event with the potential to adversely impact organizational operations, organizational assets, individuals, other organizations, or the Nation through a system by way of unauthorized access, destruction, disclosure, modification of information, or denial of service.

Cybercriminals might impersonate a remote system or user and authenticate access, and control systems. They can remotely control critical business infrastructure or transport infrastructure. Systems that organizations are building today are at risk.

- ▶ Manipulate legal history by forging digital signatures

Cybercriminals might carry out fraudulent authentication by deriving private keys from public keys. The legal underpinnings of digitalization are vulnerable because documents can be forged by using a derived private key. Also, a guarantee of proof of authorship or integrity no longer exists.

1.2 Why are quantum computers a threat

Cryptographic algorithms are based on mathematics, and with enough time and computing resources they can be broken. Improvements in cryptographic algorithms always were needed over time, as computers and digital circuits increase in speed and capacity.

However, the nature of the mathematical algorithms that can be used on quantum computers is fundamentally different from what can run on conventional computers. Unfortunately for cryptography, specific algorithms that run on quantum computers can be efficient at breaking some current cryptographic algorithms.

To help understand how quantum computers are relevant to breaking current cryptography, we first need to recognize the different types of computers and how they work. These computers are sorted into the following categories:

- ▶ Conventional computers

These computers are the computers that we use every day. Their circuits operate on binary values (bits) that can have only two states: a zero (off) or a one (on). Algorithms are implemented as sequences of computer instructions that operate on these binary values.

- ▶ Supercomputers

A supercomputer is essentially a large and tightly coupled set of conventional computers, with high-speed communications between them. They reduced or offloaded input/output (I/O) routines by design to free up CPU cycles. Supercomputers are often used to solve problems that can be deconstructed into many separate computations, which are carried out in parallel on their computing nodes.

- ▶ Quantum computers

Quantum computers process data by using an entirely different mechanism than conventional computers and supercomputers. Rather than representing data as binary values (bits) that can have only two states, the property of superposition conceptually lets quantum computers have an exponentially large number of possible compute states as more of their quantum bits (or qubits) are entangled¹¹. Hence, the more qubits a quantum computer has available, the faster it can crack cryptographic algorithms.

The computational power of quantum computers is growing rapidly. In 2021, IBM launched the 127 qubit Quantum Eagle processor with novel packaging and controls. In 2023, IBM is to debut the 1,121 qubit Quantum Condor processor to explore potential Quantum Advantages—problems that we solve more efficiently on a quantum computer than on the world's best supercomputers.

¹¹ Quantum entanglement allows qubits to be perfectly correlated with each other. Using quantum algorithms that exploit quantum entanglement, specific complex problems can be solved more efficiently than on classical computers. For the technical definition, see:

<https://quantum-computing.ibm.com/composer/docs/ixq/terms-glossary#term-entanglement>

Figure 1-1 shows the development roadmap of IBM Quantum.¹²

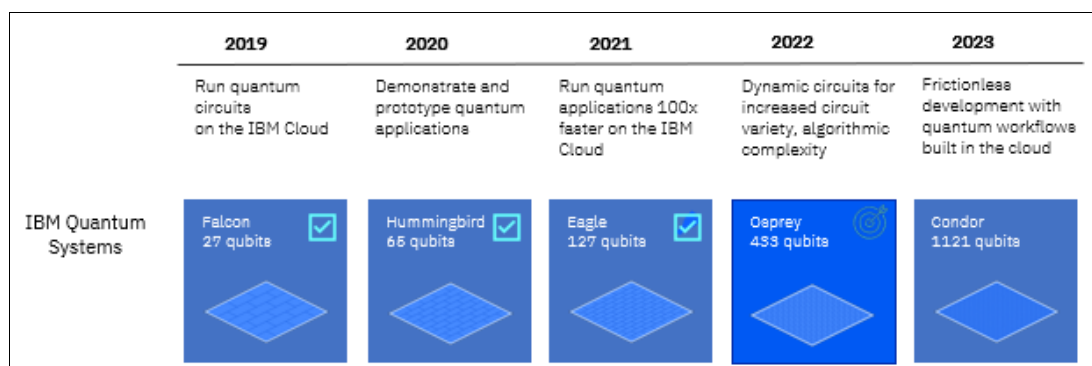


Figure 1-1 Roadmap for scaling IBM quantum technology

For a report on estimates of quantum resilience for current cryptosystems, see [Quantum Computing's Implications for Cryptography](#)¹³.

1.2.1 Cryptography overview

Various methods were used for thousands of years to protect information when it is stored or sent to other people. Early methods were simple, like the Caesar Cipher, but they increased dramatically over time, particularly as the attackers improved their ability to break the codes. The fundamental feature of all cryptographic algorithms is the use of functions that are easy to compute if you know the cryptographic key, but difficult if you do not know the key.

The cryptographic algorithms are used for the following types of protection:

- ▶ Confidentiality: This process keeps data secret from people who are not authorized to see it. The unencrypted data is called *plain text*, and the encrypted data is called *ciphertext*.
- ▶ Integrity: This ability is used to prove that data was not modified.
- ▶ Authentication: This ability is used to prove who someone is, or who created a piece of data.
- ▶ Nonrepudiation: This ability is used to prevent someone from claiming they did not create a particular specific piece of data.

The cryptographic algorithms fall into the following categories, which are described next:

- ▶ Symmetric cryptography
- ▶ Asymmetric cryptography
- ▶ Hashing algorithms

¹² See: <https://research.ibm.com/blog/ibm-quantum-roadmap-20>

¹³ National Academies of Sciences, Engineering, and Medicine. *Quantum Computing: Progress and Prospects*. Washington, DC.

Symmetric cryptography

Symmetric cryptography is used to encrypt and decrypt data. It is called *symmetric* because the same key is used for encryption and decryption. Symmetric algorithms are generally fast, and are used for everything from encrypting communications links to protecting banking transactions.

In addition to encryption of data, the symmetric algorithms are used to construct methods of providing integrity, authentication, and other operations that are important to security. For integrity, these functions are called *Message Authentication Codes* (MACs).

The following symmetric cryptographic algorithms are most commonly used today:

- ▶ Triple-DES (TDES, 3DES, or TDEA)

TDES is an older algorithm, which is gradually being phased out and replaced with the newer and stronger AES. TDES uses a key that is 112 bits or 192 bits long, and encrypts data in 64-bit blocks.

- ▶ Advanced Encryption Standard (AES)

AES use keys that are 128 bits, 192 bits, or 256 bits, and it encrypts data in 128-bit blocks. The larger key lengths and encryption block sizes make AES stronger than TDES. AES also eliminates some design issues in TDES that make TDES susceptible to specific classes of attacks.

The symmetric algorithms use complex mathematical and logical operations to combine the data and the key in such a way that the ciphertext appears to be random values. With a strong algorithm, the ciphertext cannot be examined and anything about the plain text or the key cannot be determined.

Therefore, the only way to break the algorithm is to try all possible keys until you find the one that works. On the average, this effort often means trying half of the possible keys. For example, with AES using a 256-bit key, you must try an average of half of the 2^{256} possible keys, which is a huge number.

Asymmetric cryptography

In asymmetric cryptography, which is also known as *public key cryptography*, two keys are used in combination. This configuration contrasts with symmetric key cryptography, where the same key is used for all operations. The asymmetric keys come in pairs that are known as the *public key* and *private key*, which are mathematically related.

As the names imply, the public key can be seen by anyone, while the private key is kept secret. The owner of the key generates the public and private keys together; then, it keeps the private key secret while distributing the public key to anyone who needs it. It is impossible to determine the value of the private key from the public key.

Several asymmetric cryptographic algorithms are commonly used. The two most common are Elliptic Curve Cryptography (ECC), and RSA, which is named for its inventors Rivest, Shamir, and Adleman. Unlike symmetric algorithms, differences exist in what the distinct asymmetric algorithms can do.

ECC is based on the mathematics of elliptic curves. The curves are defined by polynomials, and the ECC algorithm is based on multiplication of points on the curve. When a point is multiplied by itself, the result is another point on the curve. When this multiplication occurs many times, it is difficult to look at the final point that results from the multiplications and determine anything about the original point.

The Elliptic Curve Digital Signature Algorithm (ECDSA) is used to compute and verify digital signatures by using ECC mathematics.

The Elliptic Curve Diffie Hellman (ECDH) algorithm is used to negotiate shared symmetric encryption keys between two parties. It is notable that mathematics of ECC do not provide a way to encrypt and decrypt data. This creation is possible only by using ECC if you first create a shared encryption key by using ECDH or a similar method and then, encrypt the data by using that shared key with a symmetric algorithm, such as AES.

The security of RSA is based on the difficulty of factoring large numbers. The public key and private key are each consist of a modulus and an exponent, where the modulus is the same for each, but the public exponent and private exponent are different. The modulus is the product of two large prime numbers, and security is based on the fact that it is infeasible to factor the modulus to find those two large primes.

RSA encryption and decryption are based on modular exponentiation, where the value to be encrypted is raised to the public or private exponent, but that computation is done by using modular arithmetic that constrains the result to be less than the value of the modulus.

Whenever a value is raised to an exponent and then truncated according to the modulus, information is lost, which makes the process difficult to reverse. RSA can be used to directly encrypt data, and it is used for digital signatures by encrypting a hash of the data you want to sign. It is also frequently used to encrypt keys to transport them to other parties.

Hashing algorithms

A hash algorithm does not “encrypt” data; instead, it creates a fixed-length digital “fingerprint” (called a *hash*) from input data of any length. If even one bit of the input data is modified, the computed hash is entirely different.

Cryptographic hash functions meet two criteria: First, if you know the hash value, you cannot use it to learn anything about the content of the data that was hashed. Secondly, it is infeasible to find a different set of data that produces the same hash value.

Recommended hash functions today are the SHA-2 and SHA-3 families, which offer versions that create hashes 224 bits - 512 bits. The older hash functions SHA-1 and MD5 are no longer considered secure, although they are still in use in some applications.

1.3 Impact of Shor’s and Grover’s algorithms

When available, a sufficiently strong quantum computer can perform specific mathematical computations exponentially faster than a conventional computer or supercomputer. The most powerful conventional computer can take millions of years to solve the integer factorization problem to find prime factors for a 2048-bit composite integer.

The use of a quantum computer with Shor’s and Grover’s algorithms can break or weaken some current cryptographic algorithms. Shor’s and Grover’s are cryptanalysis algorithms when run on quantum computers.

Asymmetric algorithms derive security strength from one of three complex mathematical problems:

- ▶ Integer factorization
- ▶ Discrete logarithm
- ▶ Elliptic curve discrete logarithm

Examples of asymmetric algorithms and protocols are RSA, ECC, DH, ECDH, and ECDSA. Consider RSA, which derives its strength from the difficulty in solving the integer factorization problem. It is easy to multiply primes but difficult to take a composite integer and reduce it back to the prime factors. The difficulty in factoring rises exponentially (not linearly) as the number of bits in the key increases. The typical RSA key is 2048 bits. It is not possible with today's conventional computers to factor an integer with 2048 bits.

A sufficiently strong quantum computer can solve the factoring problems within hours with Shor's algorithm because it provides an exponentially faster method for solving integer factorization, discrete logarithm, and elliptic curve discrete logarithm problems.

Shor's algorithm has the potential to completely break the RSA and Diffie-Hellman cryptosystems and their elliptic curve-based analogs, but it cannot be used to attack symmetric encryption or hashing algorithms. Therefore, asymmetric crypto algorithms are most vulnerable to compromise.

Armed with Shor's algorithm, an adversary or cybercriminal can take a public key and derive the private key to enable impersonation and fraud attacks. Therefore, we need new algorithms that are on different math problems for conventional computers to address a CRQC attack by using Shor's algorithm.

Symmetric algorithms derive security strength from the difficulty in mounting a brute force attack or exhaustive search exploration of all possible inputs to find the answer. For cryptography, this trial-and-error technique is used to guess the correct value or key.

Examples of symmetric or hashing algorithms include AES, TDES, SHA-2, and CMAC. Brute force attacks on symmetric and hashing algorithms take a long time to search the message digest or key space to find the message digest that maps to data or correct encryption key. For example, when found, the correct key can be used to decrypt encrypted data. For a key with 256 bits, 2^{256} options exist to try in a worst case scenario.

A quantum computer can cut the symmetric algorithm strength in half by using Grover's algorithm. Grover's algorithm does not break all symmetric algorithms, but it can be used to speed up a brute force search for symmetric keys or reverse engineer a cryptographic hash. The risks to symmetric and hashing algorithms can be mitigated by switching algorithms or increasing key or hashing digest sizes because Grover's algorithm are ineffective if the search space is too large.

Grover's quantum algorithm can affect hash-based password systems because only a few passwords must be searched, and the low security level of TDEA and SHA-1 means they are both at risk.

Table 1-1 lists the current security strength of specific symmetric and hash algorithms versus post-quantum cryptography security levels. The security level and post-quantum cryptography level values are a measure of the strength that is expressed in bits.

Table 1-1 Quantum computer consequences for current cryptographic algorithms¹⁴

Security level	Post-quantum level ^a	Symmetric	Hash
<= 80	<= 40	2TDEA	SHA-1
112	56	3TDEA	SHA-224
128	64	AES-128	SHA-256
192	96	AES-192	SHA-384
256	128	AES-256	SHA-512

a. Current standards indicate that algorithm and key-size combinations that were estimated at a maximum security strength of less than 112 bits cannot provide conventional or quantum-safe cryptographic protection (see [NIST Special Publication 800-57 Part 1 Revision 5](#)).

1.4 Cryptographic vulnerabilities possible with quantum computers

All of today's approved cryptographic algorithms are strongly secure against conventional computers, including supercomputers. For example, consider AES with a 128-bit key. On the average, it takes 2^{127} guesses to find the right key. If we assume that a conventional computer can try one key every microsecond, it takes about 5.4×10^{24} years to find the key, which is not feasible. Even the fastest supercomputers can reduce this time only slightly.

However, the problem with quantum computers is that they do not have to take this approach for some of today's algorithms. In particular, the asymmetric algorithms can be broken almost instantaneously by using Shor's algorithm, even for the longest keys in use.

The advent of quantum computers makes it possible to attack algorithms by using methods that did not exist when attackers used conventional computers. Shor's algorithm with a sufficiently large quantum computer can easily break RSA or ECC algorithms. For this reason, new asymmetric algorithms are being developed that use different mathematical principles that are not subject to attack with Shor's algorithm or any other known process on quantum computers.

The risk to symmetric and hashing algorithms is significantly lower. Shor's algorithm cannot be used against these, but another algorithm that runs on quantum computers that can reduce their security.

Grover's algorithm can be used to reduce search times, and it can be used to improve brute force attacks to find a cryptographic key. When searching for something in a space of N total items, Grover's algorithm reduces the effort to \sqrt{N} . For example, a 256-bit AES key can be found with difficulty of only 2^{128} . However, this key is still considered unbreakable, and NIST and other organizations believe that AES, SHA-2, and SHA-3 provide entirely adequate security in the age of quantum computers.

¹⁴ See [The Impact of Quantum Computing on Present Cryptography](#)

Table 1-2 lists the security effect of various algorithms and protocols when a sufficiently strong quantum computer is available.

Table 1-2 Effect of quantum computing on cryptographic schemes¹⁴

Cryptographic algorithm	Type	Purpose	Quantum computer impact
AES-256	Symmetric key	Encryption	Secure
SHA-256, SHA-3	Hash algorithm	Hash functions	Secure
RSA	Public key	Signatures, key establishment	Broken
ECDSA, ECDH (Elliptical Curve Cryptography)	Public key	Signatures, key exchange	Broken
DSA (Finite Field Cryptography)	Public key	Signatures, key exchange	Broken

Organizations must consider integrating quantum-safe protection into their digital transformation strategy and application modernization plans to mitigate these two vulnerabilities with current cryptography. Consider the following points:

- ▶ Public key algorithms are broken by a large-scale quantum computer by using Shor’s algorithm. Organizations can mitigate this vulnerability by migrating to quantum-safe algorithms and schemes.
- ▶ Symmetric key and hashing algorithms are affected by a large-scale quantum computer. Grover’s algorithm cuts in half the security strengths of symmetric and hashing algorithms. Organizations can mitigate this vulnerability by increasing the key or message digest sizes.

Secure processes rely on protocols that employ public key cryptography, including those protocols that are used to secure websites for banking transactions, secure email, and signing software. It will take 5 - 15 or more years¹⁵ to replace most public key cryptosystems that are used now.

¹⁵ Refer to [Getting Ready for Post-Quantum Cryptography](#), then search for “5 to 15 or more years”

1.5 New algorithms to counter CRQC attacks

As data value grows and the required protection increases exponentially, a sense of urgency exists to protect long-lasting data from potential CRQC attacks. Organizations must safeguard data today with new cryptographic algorithms that protect against potential future CRQC attacks that might affect system integrity and core business infrastructures.

Researchers and standards bodies are moving to address the threat of CRQC attacks. They are identifying quantum-safe algorithms to protect conventional computer workloads and data.

But what makes an algorithm quantum-safe? Algorithms are based on mathematical problems with no known quantum computer speedup. Five categories of cryptographic schemes are believed to be quantum-safe (see Table 1-3). Current quantum-safe algorithm candidates are based on these schemes.

Table 1-3 Categories and examples of quantum-safe algorithm candidates

Category	Description
Lattice-based crypto	Crypto schemes from a field of mathematics that is called the geometry of numbers. The security of these schemes is based on the difficulty of solving mathematical problems over lattices; for example, the Shortest Vector Problem (SVP) and the Closest Vector Problem (CVP), such as Examples include IBM CRYSTALS-Kyber and CRYSTALS-Dilithium, Falcon.
Multi-variate crypto	A group of cryptosystems that is based on the difficulty of solving nonlinear (usually quadratic) equations over finite fields. The idea is that solving systems of equations in many variables is difficult under constraints depending on the scheme. Examples include Rainbow and GeMSS.
Code-based crypto	This cryptography uses error-correcting codes to build public key cryptography. Examples include Classic McEliece and BIKE.
Hash-based crypto	This cryptography includes digital signature schemes that are based on cryptographic hashes; for example, SPHINCS+.
Isogeny crypto	Super singular elliptic-curve isogeny cryptography is based on the isogenies or mappings between two elliptic curves; for example: SIKE.

Note: Quantum-safe algorithms run on conventional computers to protect data; the new algorithms that can break some conventional cryptography run on quantum computers. That is, quantum-safe algorithms do not run on quantum computers; instead, they run on conventional computers.

1.5.1 Quantum-safe algorithms

Currently, new cryptographic algorithms are being developed to safeguard against attacks from conventional or quantum computers. This effort is happening through a competition that is sponsored by NIST, where worldwide cryptographic experts submit candidate algorithms and analyze each other's submissions.

The algorithms are separated into the following categories:

- ▶ Digital signature algorithms
- ▶ Key encapsulation mechanisms and key-establishment algorithms

NIST indicated that after careful consideration during the third round of the NIST Post Quantum Cryptography Standardization Process, it identified four candidate algorithms for standardization. The primary algorithms NIST recommends to be implemented for most use cases are CRYSTALS-Kyber (key-establishment) and CRYSTALS-Dilithium (digital signatures). In addition, the signature schemes Falcon and SPHINCS+ also are to be standardized.

Algorithms to be standardized

For public-key encryption and key encapsulation mechanism (KEM), CRYSTALS-Kyber is to be standardized.

For digital signatures, the following algorithms are to be standardized:

- ▶ CRYSTALS-Dilithium
- ▶ Falcon
- ▶ SPHINCS+

CRYSTALS-Kyber (key-establishment) and CRYSTALS-Dilithium (digital signatures) were selected for their strong security and excellent performance, and NIST expects them to work well in most applications.

Falcon also is to be standardized by NIST because use cases might exist for which CRYSTALS-Dilithium signatures are too large. Also, SPHINCS+ is to be standardized to avoid only relying on the security of lattices for signatures.

Also, the following candidate KEM algorithms are to advance to the fourth round:

- ▶ BIKE
- ▶ Classic McEliece
- ▶ HQC
- ▶ SIKE

IBM Research® scientists were involved in the development of CRYSTALS-Kyber, CRYSTALS-Dilithium, and Falcon. They also made contributions to the development of SPHINCS+ and SIKE.

IBM implemented two of the leading finalists in this competition: CRYSTALS-Dilithium for digital signatures and CRYSTALS-Kyber as a key encapsulation mechanism. By using these algorithms, you can ensure that your data is still protected in the future when large-scale quantum computers are available. Neither of these algorithms is subject to attack by using Shor's algorithm or any other known quantum computer algorithm.

For information about these quantum-safe algorithms, see the following web pages:

- ▶ [CRYSTALS-Dilithium](#)
- ▶ [CRYSTALS-Kyber](#)

The security of these two algorithms is based on the difficulty of solving the learning-with-errors (LWE) problem over module lattices. The LWE problem involves solving a system of linear equations, where an error of ± 1 was intentionally introduced. Because of the errors, the usual methods of solving a system of linear equations do not work, which makes it infeasible to solve for the secret value.

Note: IBM Crypto Express8S (CEX8S) for IBM z16 includes implementations of the CRYSTALS-Dilithium and CRYSTALS-Kyber algorithms; the IBM Crypto Express7S (CEX7S) for IBM z16 and IBM z15™ includes CRYSTALS-Dilithium support.

For more information about the IBM Z cryptographic stack, see 4.1, “IBM Z cryptographic components overview” on page 48.

1.6 Quantum-safe capabilities with IBM Z

IBM z16 supports quantum-safe cryptography in the following ways:

- ▶ Infrastructure that protects the integrity of the system
- ▶ API functions that can be used by application programs

These methods are described next.

1.6.1 Quantum-safe infrastructure in IBM z16

IBM z16 adds features to protect the system from attacks, including threats that might use quantum computers. In particular, the system includes a secure boot feature in which it is protected with quantum-safe technology through the many firmware layers that are loaded during the boot process. Only authentic, IBM-approved firmware is accepted.

This hardware-protected verification of the firmware uses a dual-signature scheme, which uses a combination of quantum-safe and classical digital signatures. The protection is anchored in the IBM Z *Root of Trust*¹⁶.

Quantum-safe mechanisms also were added to the IBM Z cryptographic infrastructure. The Crypto Express Hardware Security Module (HSM) now uses a quantum-safe dual-signature scheme similar to the one described for the IBM Z server boot process.

Changes were made to the TKE feature to use quantum-safe cryptography when authenticating Crypto Express8S (CEX8S) coprocessors, verifying replies from the CEX8S coprocessors, and protecting key parts in flight for the Common Cryptographic Architecture (CCA). Finally, the IBM Z pervasive encryption functions were updated to use quantum-safe mechanisms for key management.

Other IBM z16 enhancements include the following examples:

- ▶ IBM z/VM® guest support for quantum-safe APIs on virtualized Crypto Express features for IBM z/OS, Linux on IBM Z, and IBM VSE
- ▶ IBM RACF® quantum-safe encrypted VSAM database support, and other base infrastructure crypto-related enhancements

¹⁶ Root of Trust is a source that can always be trusted within a cryptographic system

1.6.2 Quantum-safe API functions available to application programs

Integrated Cryptographic Services Facility (ICSF) provides APIs. ICSF is a software element of z/OS. ICSF works with the hardware cryptographic features to provide secure, high-speed cryptographic services in the z/OS environment. ICSF provides the application programming interfaces by which applications request the cryptographic services. These services include (but are not limited to) encrypting data by using software and Crypto Express HSM or CP assist for cryptographic (CPACF) functions.

ICSF offers two different cryptographic APIs for use by application programs:

- ▶ **Common Cryptographic Architecture (CCA):** An IBM proprietary API that includes general-purpose cryptographic functions and the special functions that are required by the payments industry.
- ▶ **Enterprise PKCS#11:** A standardized API that is widely used on many systems for many applications.

CCA and PKCS#11 provide API functions to support quantum-safe digital signatures by using CRYSTALS-Dilithium, and to support key agreements by using a hybrid CRYSTALS-Kyber method. You can generate the public and private keys, generate and verify digital signatures, and negotiate a shared symmetric key by using the key agreement protocol.

Although the new algorithms are needed to provide quantum-safe asymmetric cryptography, the CCA and PKCS#11 APIs contain the functions you need to implement quantum-safe symmetric cryptography and hashing.

You can encrypt data by using AES, with key sizes ranging 128 - 256 bits. You can use the SHA-2 or SHA-3 hash functions, with hash lengths up to 512 bits. In combination with the new digital signature and key agreement algorithms, this configuration gives a complete suite of quantum-safe cryptographic algorithms.

For digital signatures, one common approach today is to implement dual signatures where data is signed by using the older algorithms, such as Elliptic Curve, and the new quantum-safe algorithms. By doing so, you can meet standards that require the older algorithms, while also providing the higher level of protection that is offered by the quantum-safe algorithms. Meeting those standards is easy by using CCA or Enterprise PKCS#11 on IBM z16 because the digital signature APIs now offer both classes of signature algorithms.

Finally, the Enterprise Key Management Foundations (EKMF) key management system now supports the management of CRYSTALS-Dilithium and CRYSTALS-Kyber keys. This support allows you to manage these new key types with the same tool that was available to manage other types of cryptographic keys.



The journey to quantum protection

As discussed in Chapter 1, “Cryptography in the quantum computing era” on page 1, we are entering a new cryptographic era. The cryptographic landscape is changing about the kinds of cryptographic algorithms that are implemented across the enterprise today and the ways they are used. For most organizations, it is a journey to quantum protection. IBM is leading the way, assisting businesses and organizations on this journey.

In this chapter, we discuss some of the lessons learned as IBM embarked on the quantum-safe journey and the guidance that was provided by other organizations, such as the National Cybersecurity Center of Excellence (NCCoE), Cloud Security Alliance (CSA), and the European Telecommunications Standards Institute (ETSI). Standards are still evolving in this space and the required changes likely need significant planning and preparation. Every standard that uses public key cryptography will be affected.

IBM learned a great deal during the process of implementing quantum-safe technology in the IBM Z platform. We share some of the details of that journey and steps that can be helpful to your journey in this chapter, which includes the following topics:

- ▶ 2.1, “Quantum-safe cryptographic experiences” on page 16
- ▶ 2.2, “Starting the quantum protection journey” on page 21

2.1 Quantum-safe cryptographic experiences

IBM Z began its own quantum-safe journey and with any new technology comes new challenges. We found it necessary to survey our system landscape and at the same time use knowledge and insights from our IBM Quantum and IBM Zurich Research teams. We also engaged the broader ecosystem, including vendors, legal, and internal organizations that are outside of the IBM Z team with an interest in the subject.

The IBM Zurich Research team started several activities that were focused on developing practical cryptographic solutions that are resistant to the threats that are posed by quantum computers. With these trusted advisors, the IBM Z team has a tremendous opportunity for collaboration and co-creation of exceptional solutions.

In this section, we share IBM experiences and lessons learned (see Table 2-1) in pursuing a quantum-safe cryptographic implementation on IBM Z.

Table 2-1 IBM experiences and lessons learned

Educate the team	Build a cryptographic inventory and create a roadmap	Design and execute with cryptographic agility in mind
<ul style="list-style-type: none">▶ Educate the security teams and stakeholders▶ Follow standards for community and quantum computing▶ Learn about quantum-safe crypto options▶ Research migration best practices▶ Engage with Legal	<ul style="list-style-type: none">▶ Build cryptographic inventory (reusable security asset) where crypto is used▶ Perform a quantum risk assessment–gap analysis▶ Evaluate vendor products▶ Develop plans for use of stronger cryptography▶ Understand open source effect▶ Use a bottom-up approach	<ul style="list-style-type: none">▶ Manage internal and external dependencies▶ Make it simple to change the underlying crypto from one algorithm, method, or protocol to another▶ Remember crypto algorithms are considered secure until broken▶ Prepare for future changes▶ Develop new applications as flexible as possible to react to new developments

2.1.1 Educating the team

IBM Z developers and IBM Zurich researchers have a close relationship. Researchers serve as trusted advisers to developers. Before beginning the quantum-safe transition journey, several educational briefings were held about the topic of quantum-safe cryptography and the effects that quantum computing has on classical cryptography. These briefings served to educate IBM senior management and senior technical leadership in the IBM Z organization.

The leader's buy-in was critical for allocating the needed resources to establish the IBM Z quantum-safe transition project. A leader for the project was selected, followed by the selection of the core team.

The security stakeholders in the overall organization were then educated on the topic. It was important that the key security stakeholders be educated as their time, effort, and expertise also was required.

The project goals were set forth with the intent of establishing an enterprise-wide effort and a strategy was needed. It was important to establish a diverse group of experts from the organization, including those people responsible for hardware, firmware, software, security architecture, and secure engineering.

The core team carefully followed the National Institute of Standards and Technology (NIST) Post-Quantum Cryptography (PQC) standardization process and the activities of institutional bodies with governance over standards and regulations that are related to public key cryptography and IBM Z interests.

The core team spent time learning about the new quantum-safe algorithms and the mitigation options for various use cases. The IBM Z team researched transition best practices.

The team discussed options carefully with the IBM Zurich Research team to ensure that the proposed actions were secure. They later engaged in more detailed design sessions and created and evaluated proposals on a case-by-case basis.

As the topic of quantum-safe cryptography was starting to be understood by the industry, we found it necessary to establish our own best practices with our research colleagues. The IBM Z team also worked closely with the IBM legal team and sought their guidance to ensure the methods and actions that were taken were in line with approved guidelines.

Consultation with Legal is a common and important practice when embarking on the use of new technology as a product manufacturer. IBM Z held kickoff sessions with the technical leaders so they had some insight into the next steps in the process.

2.1.2 Building a cryptographic inventory

The next critical stage was to create a cryptographic inventory. During this process, the goal was to discover the cryptography that was in use on the platform that leads to the creation of a roadmap to address gaps.

The core IBM Z team worked with IBM Zurich Research to establish a questionnaire that was used to capture important information. The questionnaire was tailored for the IBM Z platform, including several areas, such as hardware, firmware, operating systems, virtualization, applications, solutions, and data elements.

Sessions were held with the component technical leaders to answer any questions they might have about the questionnaire, and how the questionnaire was to be completed. Each component leader worked with their team to complete the questionnaire and return it to the core team. The questionnaire covered nine key areas that were related to cryptography and cybersecurity in general (see Table 2-2 on page 18).

Table 2-2 Cryptographic inventory questionnaire

Area	Information collected
Identity	<ul style="list-style-type: none"> ▶ Name of component or application ▶ Feature or function that uses crypto ▶ Person responsible for component and contact information
Symmetric crypto	<ul style="list-style-type: none"> ▶ Algorithm ▶ Function (encryption, decryption) ▶ Symmetric key size ▶ Length of time data needs to be kept secret ▶ Sensitivity level of the data protected (H/M/L)
Asymmetric crypto	<ul style="list-style-type: none"> ▶ Algorithm ▶ Function/protocol/method ▶ Asymmetric key size
Hashing	<ul style="list-style-type: none"> ▶ Algorithm ▶ Digest size
Crypto services	<ul style="list-style-type: none"> ▶ Crypto provider ▶ Crypto provider product version ▶ Vendor name ▶ How is crypto provided? (HSM, software library) ▶ How is the crypto implemented? (hardware, software) ▶ How is crypto provider version kept current?
Interoperability	<ul style="list-style-type: none"> ▶ Do you control the full stack? ▶ Do you work with a vendor or partner? ▶ Is the partnership internal or external to the team or organization?
Policies/standards/regulations	<ul style="list-style-type: none"> ▶ Are there policies governing the selection and use of the cryptography? If so, which? ▶ Are there standards or regulations governing use of the cryptography? If so, which? ▶ Are there associated configuration files? ▶ Can the component's crypto "state" or status, configuration status, and so on, be queried or monitored? ▶ Consider cyber resilience: Are there single points of failure or simple denial of service (DoS) choke points?
Key management	<ul style="list-style-type: none"> ▶ Where do the keys come from? ▶ Where are the keys stored? ▶ Is a key management system or key server used? ▶ Is a key transport protocol used? ▶ Are the derived or created keys used to wrap or protect other keys?
Preliminary assessment	Has a gap been identified? (Crypto being used must be updated, mitigation plan is needed?)

Each component leader was asked to gather this information and provide for review by the IBM Z core team. Other information might need to be included in the questionnaire by your organization; however, Table 2-2 on page 18 is a good place to start.

The IBM Z core team reviewed the questionnaires and helped each component team develop preliminary plans for the use of stronger cryptography for symmetric crypto and hashing or quantum-safe crypto schemes for asymmetric crypto. IBM Z looked at areas where crypto was being used and looked for places where cryptographic protections might be added.

This iterative process led to fruitful discussions. Design review sessions were held, and research provided guidance and feedback about the plans and strategies that were developed. Because the cryptographic inventory is a living document, the inventory documentation must be updated as changes are made.

2.1.3 Creating a roadmap

After the IBM Z core team understood the affected areas, it was necessary to prioritize the changes. We developed a multi-phase roadmap with the goal to update protections of the most important areas first.

The IBM Z team also considered areas where the changes were simpler to make. Some items needed to be implemented day one and some items were to be updated over time. Several factors influenced the decisions about where items land on the roadmap.

Evaluating dependencies was critical. The uncertainties, costs, and the value of the option to the system also needed to be considered. The core team had dependencies inside and outside IBM Z, which affected prioritization of changes.

Some of the dependencies included the following examples:

- ▶ NIST PQC Standardization Process algorithm recommendations
- ▶ Other standards and guidelines not yet updated; for example, IETF community, including:
 - TLS/SSL/SSH standards
 - PKI standards for certificates
 - network security
 - communication protocols
- ▶ Availability of quantum-safe hardware products from vendors
- ▶ Dependencies on IBM software and hardware solutions
- ▶ Availability of crypto libraries and hardware that supports the quantum-safe algorithms

The IBM Z approach was to protect the system infrastructure (such as core boot paths and related firmware components) and key security components, such as the Crypto Express hardware security module (HSM) and Trusted Key Entry (TKE). At the same time, customers had to be provided with the capabilities to begin the use of and experimenting with the quantum-safe technology. The IBM Z team considered areas where we controlled the entire stack and dependencies were internal to our system. Implementation complexity might be a function of technology or unresolved dependencies.

After prioritizing the work based on the risks and dependencies, a multi-phase roadmap was created. Flexibility was maintained in the roadmap as discoveries during the plan execution phase were expected.

2.1.4 Designing and running with cryptographic agility in mind

The key to the designs was the need to include cryptographic agility. This became evident because of some uncertainties that were identified early in the process and the necessity to create designs that lend themselves to change with new crypto algorithms in the future.

During the execution phase, the IBM Z team used the following options that were based on the identified use cases:

- ▶ Updated encryption by migrating to AES encryption by using 256-bit keys
- ▶ Updated hashing algorithms to support SHA-256 or higher
- ▶ Implemented dual digital signing schemes by using classical and quantum-safe algorithms
- ▶ Implemented hybrid key exchange mechanisms by using classical and quantum-safe algorithms

At this stage of the quantum-safe journey, these options were the most reasonable for the use cases.

The IBM Z team identified all of the operating environments where algorithm support and secured quantum-safe libraries were needed. Vendors were contacted to understand their quantum-safe roadmaps and plans. Based on feedback from these vendors, the IBM Z roadmap was revised.

Discussions with the IBM Zurich Research team, the IBM Quantum team, the IBM Security® team, and IBM Legal team continue as changes were implemented and next steps were documented.

IBM Z designs were created with agility in mind to be prepared for the transition when new standards guidance is provided and to support inevitable future changes to cryptographic algorithm requirements. The purpose also was to lay a foundation for which IBM Z can make the other areas of the system quantum-safe over time.

2.1.5 Quantum-safe journey in review

This high-level overview of the journey that was taken by IBM Z can be used to help start your quantum-safe journey. The IBM Z journey and the recommendations of other experts in the IT industry included the following takeaways:

- ▶ Obtain senior level management buy-in
- ▶ Educate your organization on quantum risks and quantum-safe cryptography
- ▶ Create a quantum-safe crypto core team
- ▶ Inventory current crypto in use
- ▶ Control access to the inventory
- ▶ Identify areas that are most vulnerable
- ▶ Research cryptographic agility and quantum-safe cryptographic algorithms to determine which algorithms suit your use cases
- ▶ Identify crypto API providers and crypto hardware to accelerate performance
- ▶ Develop implementation validation and testing tools
- ▶ Identify all communications protocols with quantum-vulnerable crypto algorithms
- ▶ Identify automated crypto discovery tools
- ▶ Update the processes and procedures of developers, implementers, and users

- ▶ Develop a risk-based approach, considering security requirements, business operations, and mission impact
- ▶ Identify a transition timeline and resources
- ▶ Prepare to follow strategies to protect digital assets and systems

2.2 Starting the quantum protection journey

Several stages must be taken along the journey. Each organization has different cryptography use cases and usage constraints. It is important that the collateral that is created by each team be reviewed to provide the best options and plans for your situation.

Although no one-size-fits-all solution exists, general steps and guidance can be beneficial. Consider your cryptographic use in three broad areas:

- Infrastructure
- Applications
- Data protection

2.2.1 Following industry guidance

Several organizations formed task forces or working groups to discuss quantum-safe cryptography and offer their guidance. We recommend that you review the work being done by these groups. Experts in the field provide insights that can prove to be useful in your situation.

National Cyber Security Center of Excellence (NCCoE)

NCCoE formed a Post-quantum cryptography (PQC) project. The project goal is the development of practices in the form of white papers, playbooks, and demonstrable implementations for organizations to ease the transition from the current set of public key cryptographic algorithms to replacement algorithms that are resistant to quantum computer-based attacks.

For more information, see this [NCCoE web page](#).

Electronic Telecommunications Standards Institute (ETSI)

The ETSI Cyber Quantum Safe Cryptography (QSC) Working Group aims to assess and make recommendations for quantum-safe cryptographic primitives, protocols, and implementation considerations. These considerations are based on the state of academic cryptography research and quantum algorithm research, and industrial requirements for real-world deployment.

For more information, see this [ETSI web page](#).

Cloud Security Alliance (CSA)

CSA formed a quantum-safe security working group. The goal of this working group is to support the quantum-safe cryptography community in the development and deployment of a framework to protect data that is in movement or at rest.

For more information, see this [CSA web page](#).

French National Cybersecurity Agency (ANSSI)

ANSSI is committed to ensuring that public administrations, public services, and businesses can take full advantage of a secure and trustworthy digitalization. The goal is to provide direction to industrials developing security products and outlining the transition agenda for quantum-safe cryptography.

For more information, see this [ANSSI web page](#).

2.2.2 Start now

The threat that quantum computers pose to our current cryptographic systems is well known. Even though large-scale quantum computers are not yet here, it is critical to take action well before their arrival. Organizations need to be planning now, for the upcoming transition to new quantum-resistant cryptographic algorithms. Failure to do so may mean that your information will not be protected from these future attacks.

- Dustin Moody, Mathematician, Post-Quantum Cryptography Project Leader, National Institute of Standards and Technology (NIST)

For the last several years, experts were urging organization to begin planning for the replacement of hardware, software, and services that use the cryptography that is likely subject to attack by a quantum computer.

Based on history, it can take a long time to make changes in all the places where change is required. The initial inventory phases can show surprising findings. This part of the process is often referred to as *crypto discovery*. Not only do you find crypto that must be migrated, but you might also find areas where cryptographic protections are not in place or that cryptography is not correctly implemented and not suitable for the intended purpose.

You might discover that specific source code is no longer available or build tools are no longer available, which makes change difficult and time-consuming. It is advantageous to find automated tools that help with the inventory process.

The authors of code modules might be unknown or no longer work for the company. The new algorithms are not drop-in replacements. Key sizes, signature sizes, performance, and so on must be considered.

Any number of your IT professional staff might need to get involved in your quantum-safe journey (see Table 2-3 on page 23 for examples).

Table 2-3 Involvement of IT professionals for the quantum-safe cryptography journey

Stakeholder	Roles
IT security	<ul style="list-style-type: none"> ▶ Chief information security officer ▶ Chief security architect ▶ Key management personnel ▶ IT security personnel ▶ Mainframe security administrator ▶ Enterprise security Architect
Networking	<ul style="list-style-type: none"> ▶ Network administrator ▶ Network architect
Auditors	<ul style="list-style-type: none"> ▶ Security auditor ▶ Financial regulation office ▶ Compliance officer/auditor
Applications	<ul style="list-style-type: none"> ▶ Application architect ▶ Application programmer ▶ Application owner
Management systems	<ul style="list-style-type: none"> ▶ System administrator ▶ Hardware administrator ▶ Storage administrator
External parties	<ul style="list-style-type: none"> ▶ Customers ▶ ISV representative ▶ Business partners

Another important reason to start the quantum-safe journey now is because you do not want to keep creating assets that are susceptible to quantum attacks. Use protection methods today so that today's data is protected in the future. New technology takes time to develop, test, and deploy. To avoid costly mistakes and to ensure you have the technology to address your use cases, organizations must start *now*.

2.2.3 Building your inventory

Consider creating a data inventory and cryptographic inventory:

- ▶ The data inventory must contain information about your critical data assets. It is a comprehensive catalog of the data assets in the enterprise.

Document important information about the data protection requirements and how long that protection must be in place. Also, record any standards or regulations that govern the protection of the data.

- ▶ The cryptographic inventory must contain information about where and how cryptographic algorithms are used.

The cryptographic inventory provides you with the information you need to create your roadmap and plan. In specific cases, tools do not exist that automate the process of inventorying the crypto in use.

Using a questionnaire

A questionnaire can be a useful tool for gathering the information from the key stakeholders. The questionnaire helps stakeholders understand for what they need to look. The questionnaire can be used with the tools that are available to compile the baseline inventory. IBM Z provides tools that can help with crypto discovery. For more information, see "Establishing a cryptographic inventory" on page 58.

Maintaining and securing the inventory

Maintaining and securing the inventory is critical. Make sure you treat the inventory as the security-sensitive artifact that it is. Access to the contents must be controlled. Component owners can access their information but not the information of other components unless a need to know exists and collaboration among teams is needed.

Performing a gap analysis

By using the inventory, you can perform a gap analysis that leads to the creation of your roadmap. More than likely, you discover that you cannot change every area that is identified in your inventory. Therefore, you must prioritize.

Protect the most critical assets first and make changes so that you do not continue to use vulnerable cryptography where possible.

Determining dependencies

Dependencies can determine the location and timing of changes on your roadmap. You must have a mitigation strategy in place. This strategy includes knowing the mitigation options that are available to you and when to use those mitigations.

It is critical that your strategy include extensive testing. Solutions must be prototyped to understand usability and performance effects. Some of the mitigations involve the use of longer keys and artifacts, which requires more space and resources. It is critical that you review your threat models with your secure engineering team to ensure you did not inadvertently introduced a vulnerability.

2.2.4 Knowing your options

After you understand where crypto is being used, it is critical to know your mitigation options. A transition strategy is needed that is based on industry guidance and the use cases that your organization must address. It is important to perform a risk assessment to inform your decisions about your transition roadmap.

The primary options include the following examples:

- ▶ Strengthening symmetric and hashing algorithms by increasing key sizes for strong algorithms, such as AES, to at least 256 bits and hashing digest sizes to at least SHA-256, depending on your use case.
- ▶ Implement dual signing. A dual signature consists of at least two signatures on a common message. According to guidance provided by NIST, one signature is generated with a NIST-approved signature scheme as specified in FIPS 196, while the other signatures can be generated by using a different signature algorithm.

For quantum-safe, the second signature is a quantum-safe signature (CRYSTALS-Dilithium is used for IBM z16). The signatures must be parsed and verified separately; if either fails, the signature for the object fails.

- ▶ Implement hybrid key establishment schemes. This scheme is a combination of two or more components in which cryptographic key-establishment schemes are used.

According to guidance from NIST, the scheme is considered secure if at least one of the schemes remains secure. Therefore, one of the components of the hybrid scheme must be NIST-approved; for example, a discrete-logarithm based scheme from NIST SP 800-56A or an integer-factorization scheme from SP 800-56B, and the other component is a post-quantum cryptography scheme.

NIST SP 800-56C describes a hybrid key establishment construction. The specification describes a process that allows a key derivation method permitting a shared secret¹ “Z” to be concatenated with a value protected by a quantum-safe key encapsulation mechanism (KEM).

Each specific use case must be evaluated to determine whether the implementation costs, performance reduction, and solution complexity can be contained. The hybrid and dual schemes require a security review to ensure that the security-related implementation errors were not introduced.

For more information about common cryptography use cases with challenges a cryptographically relevant quantum computer (CRQC) can present and the quantum-safe solutions that are provided by IBM Z, see Chapter 3, “Using quantum-safe cryptography” on page 27.

2.2.5 Incorporate cryptographic agility

It has probably become clear that piece by piece, enterprises must change the underlying cryptography that they use. However, this instance is not the last time such a change is required. This necessary change is an opportunity to rethink how applications use complex cryptography such that future changes, updates, and patches are much simpler to apply.

Cryptographic agility is the key for cybersecurity.

When we think of cryptographic agility, we must broaden our view of its scope beyond cryptographic migration such that we focus on only swapping from one crypto algorithm or standard to another because of the complexity of the problem. We must think about how we transition to architectures that offer agility for ongoing cryptographic migrations over time.

We know that cryptographic algorithms break or become obsolete. IBM Think® of the dimensions of cryptographic agility as areas where we can focus on agility. The topic of agility is relevant throughout the lifecycle of crypto from its definition and introduction into standards through its retirement as being obsolete or no longer secure.

The early phases of a cryptographic algorithm's lifecycle are handled by experts in the field in academia and industry. Table 2-4 lists the cryptographic agilities that are most important to our discussion.

Table 2-4 Cryptographic agilities

Agility	Definition
Algorithm	Ability to select algorithms in real time based on their combined security functions or organizational policy
Protocol	Ability to move to new versions of a protocol, such as 1.1 to 1.2 to 1.3, for TLS
Implementation	Ability to add crypto features or algorithms to hardware or software, which results in new, stronger security features
Platform	Ability to adapt to platform-specific constraints or support for cryptographic operations
Retirement	Ability to retire crypto systems that became vulnerable or obsolete

¹ Known only to the entities involved in a communication. Possession of that shared secret can be provided as proof of identity for authentication.

Cryptographic agility is an active area of research. Guidance that we see coming out of research areas already recommends no longer hardcoding crypto specifics in applications. Instead, the use of a higher-level abstraction layer allows for passing in those specifics so that they can be changed when needed without changing the application when possible.

From a broader standpoint, cryptographic agility is about an information security system's ability to rapidly switch to alternative cryptographic primitives and algorithms without making significant changes to the system's infrastructure.

When considering your cryptographic strategy in light of quantum-safe transition, spend some time studying this topic and explore how to best improve your cryptographic agility.

For more information and an example, see "Considering cryptographic agility" on page 61.



Using quantum-safe cryptography

In this chapter, various use cases are introduced to illustrate the threats that many organizations face with the rise of quantum computing for use cases that are related to confidentiality, integrity, authentication, and nonrepudiation.

Across these use cases, the challenges are addressed and how the quantum-safe capabilities that are provided with IBM z16 can help to overcome these challenges and ensure the security of sensitive and valuable data into the future.

Also, each use case includes applications for quantum-safe encryption capabilities across different industries and the specific enhancements with IBM z16 that enable these adoption patterns.

This chapter includes the following topics:

- ▶ 3.1, “Protecting sensitive data” on page 28
- ▶ 3.2, “Use case: Sharing keys securely” on page 31
- ▶ 3.3, “Use case: Message integrity and secure logging” on page 37
- ▶ 3.4, “Proof of authorship” on page 42

3.1 Protecting sensitive data

Classical cryptographic algorithms are widely used to protect data that is at rest and in flight. Cryptographic algorithms are used for having the capabilities of secrecy, integrity, authentication, and nonrepudiation.

Organizations use symmetric keys and public key encryption for data protection schemes. Most organizations encrypt sensitive data to protect it against insider threats, unauthorized user access, and accidental data exposures.

An organization's data is at risk on the internet and communication network when Shor's quantum algorithms are used to break public key encryption schemes. Suppose that a cybercriminal gets access to a powerful quantum computer, they can decrypt lost or harvested confidential data by determining encryption keys.

In highly regulated industries, organizations must protect subject data rights to personally identifiable information (PII) or personal health information (PHI) and comply with standards, such as GDPR, NIST, ISO, SOX, CCPA, and PCI. Data privacy and security are critical to avoid penalties and the cost of data breaches because digital trust and brand reputation are at stake. Organizations need quantum-safe encryption to protect their sensitive data and maintain the confidentiality of trade secrets in the quantum era.

3.1.1 Problem statement

An organization's long-lasting data can be at risk from "harvest now, decrypt later" attacks. These attacks are carried out offline or as passive attacks on confidentiality versus as an online attack against a security protocol. That is, an adversary might carry out the attack by collecting data or public information today and later attempt to recover the secret key that is used to encrypt the data. This process might be done by mounting a brute force attack to find the secret key. The the private key that is used in a key negotiation step also might be derived by attacking Rivest, Shamir, Adleman (RSA) or Elliptic Curve Cryptography (ECC) if a public key protocol was used for secret key establishment. The bad actor's goal is to find the secret key that was used to encrypt the data.

Organizations must start the use of quantum-safe methods to protect their data now so that more vulnerable data is not produced. Several symmetric algorithms are not secure when Grover's algorithm is used to search the key space.

Organizations can mitigate the risk by switching to strong encryption algorithms, such as AES, and ensuring the AES key length is at least 256 bits. As discussed in "Cryptographic vulnerabilities possible with quantum computers" on page 9, organizations should not continue to encrypt their sensitive data by using algorithms, such as 2TDEA or 3TDEA, whose strength is not sufficient in the quantum computing era. These algorithms for new encryption use cases must be retired or no longer used when possible.

3.1.2 Solving this challenge by using IBM z16 capabilities

Organizations must be concerned about data protection today. Even though the threat of a quantum computer might be in the future, organizations must ensure that they are not continuing to create encrypted data by using methods that are not quantum-safe, especially for long-lasting data.

It is essential to understand data classification and where potential exposures exist. It is also critically important to have a plan for retiring versions of your data that were protected by using the retired algorithms. If that data remains in systems, an attacker might find it and break it without attacking the version that is newly protected with the newer algorithm.

In 2.2.3, “Building your inventory” on page 23, we discussed creating a data inventory and a cryptographic inventory. These security assets help organizations identify which data is encrypted and which encryption methods were used.

The inventories must be reviewed to highlight weak or vulnerable encryption cryptography that is used in the enterprise to protect data. IBM provides tools to help create the cryptographic inventory, such as ADDI, CAT, zERT, and the Crypto Statistics Monitoring tool, as described in “Establishing a cryptographic inventory” on page 58.

After the vulnerable data assets are identified, a data protection strategy is created. The strategy is informed by using knowledge about how the data must be protected.

IBM z16 offers several features that can be used to protect the data, such as pervasive encryption. This encryption feature uses AES encryption with 256 bits. Its internal key management support uses quantum-safe protections with a hybrid key exchange mechanism that uses CRYSTALS-Kyber and Elliptic Curve Diffie Hellman (ECDH) and dual-signing scheme that uses CRYSTALS-Dilithium and Elliptic Curve Digital Signature Algorithm (ECDSA). The pervasive encryption features include Linux on IBM Z protected key dm-crypt, z/OS data set encryption, coupling facility encryption, and IBM z/VM encryption.

IBM z16 also provides quantum-safe APIs that can be used to protect data. The APIs are available through ICSF. IBM z16 provides quantum-safe key management APIs and lifecycle management support for the organization to generate the encryption keys and also encryption APIs that can be used to encrypt the data (see Figure 3-1).

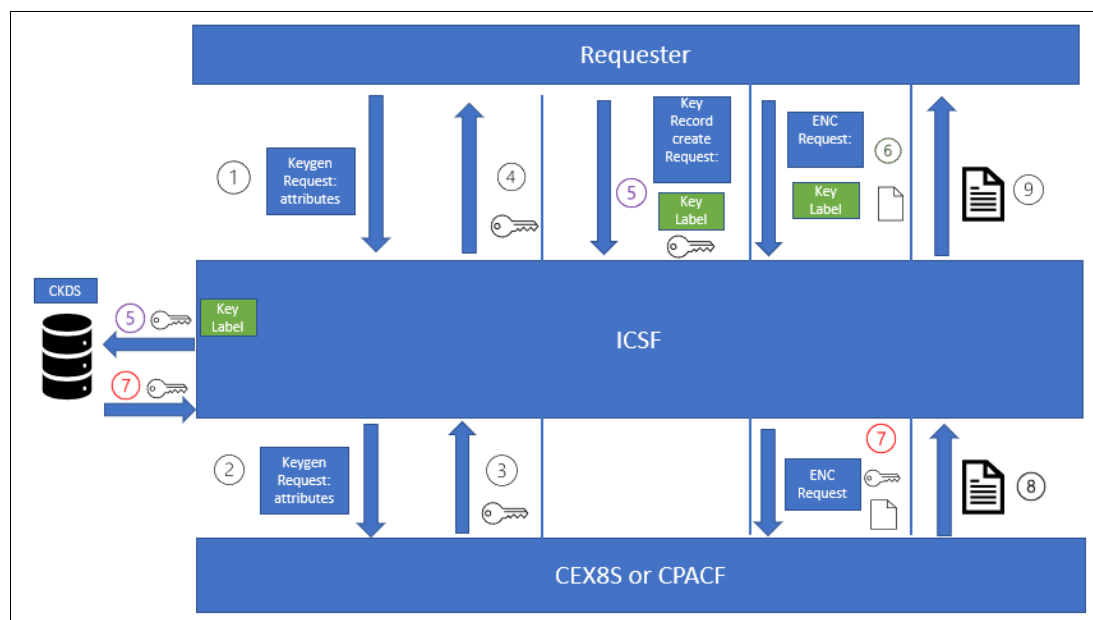


Figure 3-1 Data encryption process

The following process is used to encrypt data on the IBM z16 as shown in Figure 3-1 on page 29:

1. The Requester calls ICSF to generate an AES 256-bit CIPHER key. The Requester is a component that uses the quantum-safe APIs, such as an application or key management tool.
2. ICSF sends a request to Crypto Express8S (CEX8S) to generate a secure key.
3. CEX8S returns the secure key to ICSF.
4. ICSF returns the key to the Requester.
5. The Requester calls ICSF to add a key record to the CKDS that contains the key, which later is referenced by its associated key label.
6. The Requester calls ICSF to encrypt data by using the key label.
7. ICSF retrieves CIPHER key from the key data set. If requested, the secure key is converted to a protected key. A secure key request, including the key and data, are sent to the CEX8S. Protected key requests (including the key and data) are sent to CPACF.
8. The crypto engine (CPACF or CEX8S) returns the ciphertext to ICSF.
9. ICSF returns ciphertext to the Requester.

3.1.3 Industry applications

In highly regulated industries, organizations must provide data security and protection to meet the privacy regulations and compliance requirements that are outlined in their data retention policies. Examples are healthcare and insurance organizations with patient health information (PHI) in electronic medical records (EMR) that must be protected. These and other organizations must encrypt and store confidential documents for a long period.

Information that requires special attention includes tax documents, legal agreements, trade secrets, and clinical trials. Customer data and PII must be protected. Financial and banking organizations must protect customer data in mortgage and loan processing applications. They must also safeguard banking (PAN data) or payment card (IBM PIN® data). Organizations must ensure that their data is being protected by using quantum-safe encryption methods.

3.2 Use case: Sharing keys securely

This use case describes the requirement for organizations with confidential information, such as intellectual property, to share their sensitive data with Business Partners and third parties by establishing keys with traditional key exchange protocols.

In addition, the threat that quantum computing has on these processes are explained in-depth and how IBM z16 capabilities can overcome these challenges. The quantum-safe capabilities in the IBM z16 can help ensure that partnering organizations securely share their intellectual property and proprietary information to avoid information disclosure and protect it from competitors to avoid reputation damage, profit loss, and brand impact.

Across many industries, organizations use their valuable information, sensitive data, and intellectual property to compete and succeed in a global market. These digital assets oftentimes constitute over 80% of the organization's total value.

Organizations that have strategic relationships with each other, such as Business Partners, often need to share this valuable information to collaborate and develop solutions and products. As important as it is to enable this collaboration and allow for sharing of information, it is equally important that this valuable information stays out of the hands of competitors and adversaries. The unintended disclosure of an organization's intellectual property and sensitive information can result in irreversible damage to the organization's reputation, along with profit loss and long-lasting brand impact.

Traditionally, organizations keep their sensitive information and digital assets protected by encrypting their data within their data boundaries. The ability to share these encrypted assets with partners implicates a need to securely share keys with their partners so that they can also access the data. This process is referred to as a *key exchange* and often used a key agreement protocol. The details of a hybrid key agreement scheme are described in this section.

3.2.1 Problem statement

In the past, this key exchange process was used by partnering organizations in a way that allowed them to securely derive the same encryption key over a public, insecure channel. Regardless of who was eavesdropping on the public channel (whether a competing organization or a bad actor), the mutually derived encryption key maintained its confidentiality because of the ability to establish a secure connection over this public, insecure channel by way of key exchange schemes.

Traditionally, the ECDH key agreement protocol is a method that is used to derive keys for a key exchange process. This key agreement scheme allows two business parties, each with their own ECC key pair (consisting of a private and public key) to establish a shared secret by using an insecure channel, and it begins with each party sharing their public keys.

However, a key agreement scheme solves one piece of the key exchange puzzle. To create a truly secure key exchange protocol, you must also solve the "trust" problem that is associated with exchanging keys.

Although the public key can be shared over an insecure channel, a mechanism must be in place to ensure that the key that is labeled as party A's public key really belongs to party A and the key labeled party B's public key really belongs to party B to avoid a man-in-the-middle attack.

This problem can be addressed by cryptography; however, this use case focuses on the key establishment piece of the key exchange puzzle. For our example, we assume that a trust mechanism is in place.

If party A and party B wanted to participate in a key exchange process to obtain a shared key, they each generate their ECC public-private key pair and share their public keys with each other. Each party can use the ECDH protocol to derive the same shared key.

For example, party A uses their private key in combination with party B's public key in the protocol, while party B uses their private key in combination with party A's public key. The result is that both parties now have the same shared secret. This method of key exchange to derive the same shared secret historically was considered secure because neither party had to share their private key to perform the key exchange.

Traditionally, this use of public key cryptography for key exchange was considered sufficiently secure. The only means for a cybercriminal to derive the shared secret key was to obtain one of the party's private keys.

Although the public and private keys in an ECC key pair are mathematically related, it takes a conventional computer millions of years to derive the private key from one party's public key because of the significant computational capacity that is required to perform this operation. However, the rise of quantum computing brings about many challenges to keeping the shared secret key secure.

Although specific symmetric key algorithms, such as AES with 256-bit encryption keys, are considered quantum-safe, the method of sharing those keys in a key exchange by way of public key cryptography is no longer considered to be quantum-safe, which results in the vulnerability of these symmetric keys.

After quantum computers have the computing power to perform Shor's Algorithm, an adversary with access to a quantum computer can solve the elliptic curve discrete logarithm problem exponentially faster than a conventional computer. As a result, the private key of one party can be derived from their public key in only a matter of hours.

After the key is in the hands of an adversary, the same shared key that is derived by the two parties might be generated with the ECDH key exchange scheme. Then, the bad actor can access the organization's valuable information.

To make matters worse, data that is encrypted today by using symmetric keys that are exchanged between two parties by way of public key cryptography is still not safe, even in the absence of quantum computers of sufficient scale.

Because the encrypted data, along with the public key, can be harvested today, an adversary with access to a quantum computer in the future can perform Shor's algorithm to break this public key cryptographic algorithm to expose the sensitive data.

3.2.2 Solving this challenge with IBM z16 capabilities

Valuable information and digital assets that partnering organizations share with each other are no longer secure because of methods that are used by adversaries to harvest the encrypted data now.

IBM z16 provides quantum-safe capabilities to circumvent this security challenge and allow for the secure key exchange between two parties in a quantum-safe manner. With IBM z16, organizations have a reliable method to securely share encryption keys between parties through a hybrid key exchange scheme.

Although traditional key exchange schemes relied on public key cryptography alone to derive a shared secret, a hybrid key exchange scheme relies on classical cryptography (such as ECDH) and a quantum-safe cryptographic algorithm (such as CRYSTALS-Kyber). ECDH is a key agreement protocol and CRYSTALS-Kyber is a key encapsulation mechanism.

When used together, organizations have an efficient way to securely exchange keys, even in the face of high-powered quantum computers. This secure exchange is made possible with the introduction of quantum-safe APIs within the Crypto Express8S feature (CEX8S). This feature is provided with IBM z16 to securely derive quantum-safe encryption keys by using the hybrid key exchange mechanism that is performed in the CEX8S by using the CCA API or the Enterprise PKCS#11 API.

When two Business Partners (party A and party B) take advantage of this hybrid key exchange scheme on IBM z16, they can safely derive keys that are used to protect their shared sensitive information (see Figure 3-2).

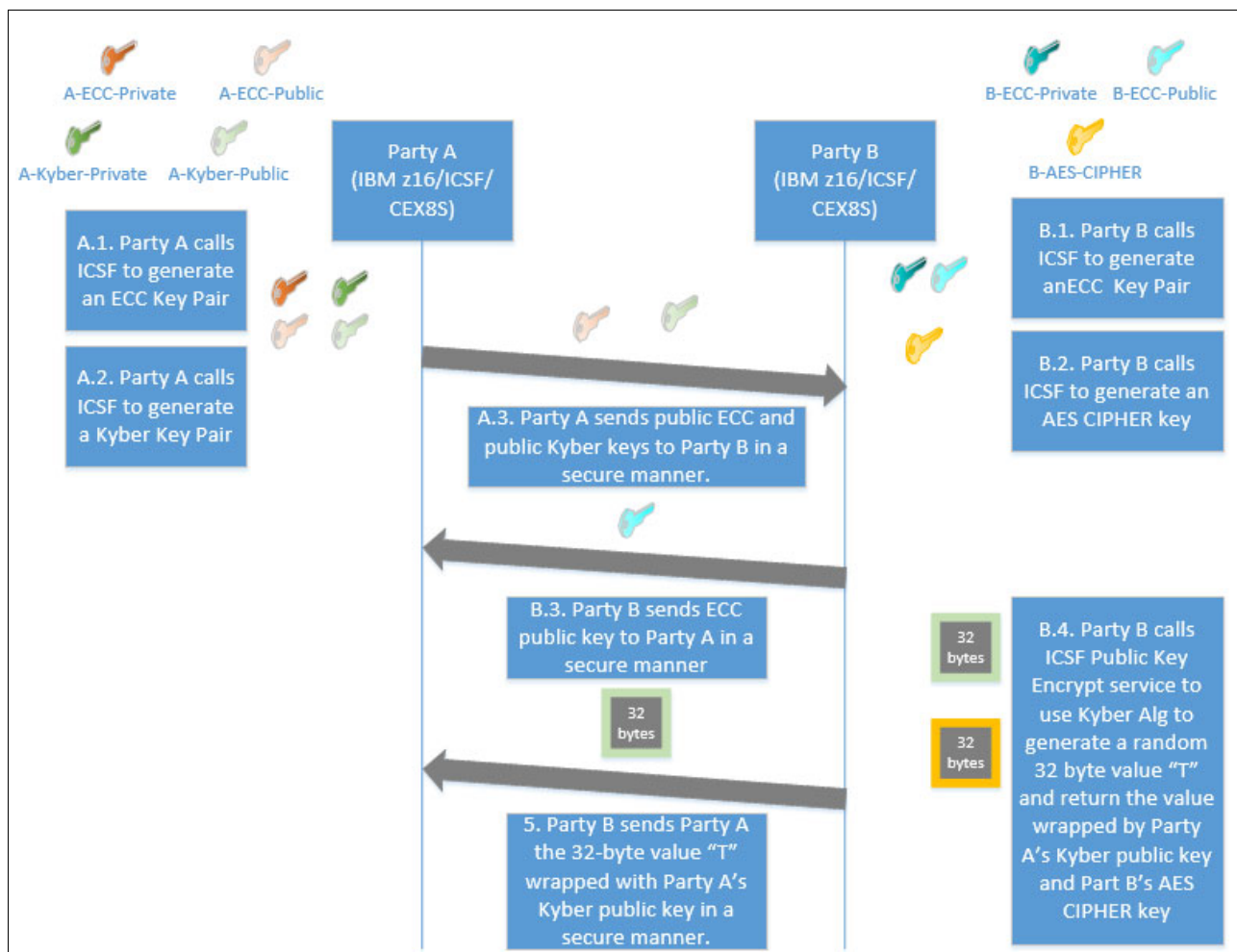


Figure 3-2 Key and data setup for hybrid key exchange - CCA example

By using this capability, party A generates an ECC key pair and a quantum-safe CRYSTALS-Kyber key pair. Party B must generate an ECC key pair and an AES CIPHER key. The two parties then exchange their public keys.

Party B then uses CEX8S APIs to generate a random 32-byte secret and encrypt it with party A's CRYSTAL-Kyber public key and an AES key that is owned by Party B. The secret that is protected with the CRYSTAL-Kyber public key is transmitted to party A. Although it is being sent over an insecure channel, not even a quantum computer can break this algorithm because it is considered to be quantum-safe (see “New algorithms to counter CRQC attacks” on page 11).

After party A receives the wrapped secret, they then use their CRYSTALS-Kyber private key to recover the 32-byte secret from party B. Now that both parties have each other's ECC public key and the 32-byte secret, they can each use the ECDH key agreement protocol to create a shared secret just as they do in the classical key exchange process (see “Quantum-safe hybrid key exchange” on page 113).

However, this shared secret is used with the mutually known 32-byte secret in the key material creation process to compute the same shared key by using ECDH. This 32-byte secret is protected with the quantum-safe Kyber algorithm. By using the CEX8S APIs, the secret information is protected by the hardware security module and never appears outside in the clear in the memory of the host computer.

After this shared secret key is derived by both parties, it can be used to encrypt either party's data, and the data itself can be shared between parties (see Figure 3-3). Even in the presence of a quantum computer with sufficient computing power, the key cannot be derived. Although a quantum computer might derive either party's ECC private key, the 32-byte secret that is used in the ECDH protocol cannot be exposed because it was protected by using a CRYSTALS-Kyber key.

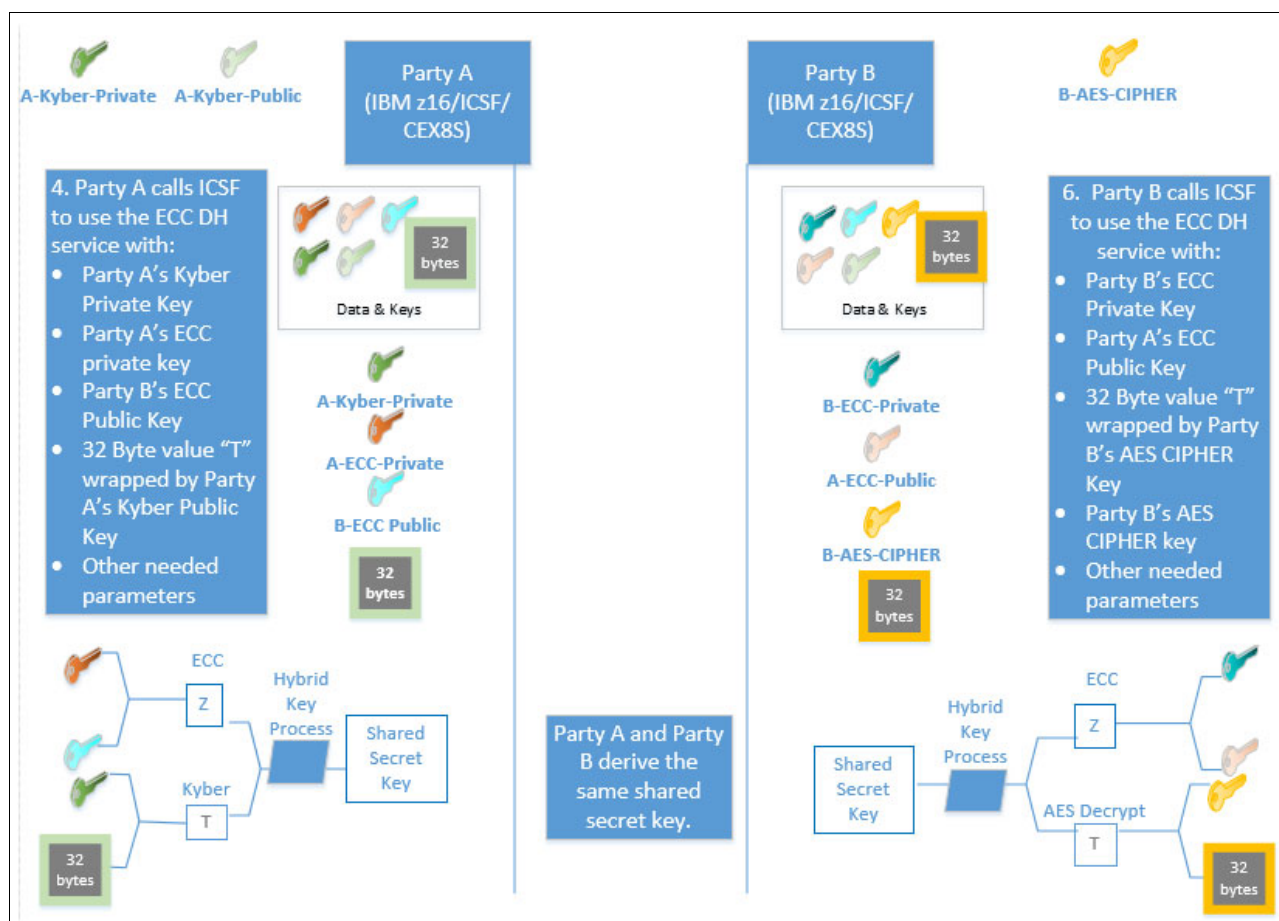


Figure 3-3 Hybrid key agreement process - CCA example

3.2.3 Industry applications

This section describes how organizations across many different industries with a need to share encryption keys securely with partners by using traditional key exchange mechanisms might be vulnerable to CRQC attacks.

It also outlines how they can benefit from the hybrid key exchange schemes that are provided with IBM z16 to ensure data confidentiality, even in the presence of sufficiently capable quantum computers.

Pharmaceuticals

The pharmaceutical industry is an example of the need to securely share intellectual property and research findings with Business Partners to drive success. The process of developing new drugs and making them publicly available in the marketplace is lengthy and costly.

On average, it takes at least 10 years for a new drug to become available in the market, with six to seven of those years being dedicated to performing clinical trials. A study that was conducted by Tufts Center for the Study of Drug Development¹ estimated that it costs pharmaceutical companies \$2.6 billion to develop a new medication gaining marketing approval.

Pharmaceutical companies that are vying to successfully complete clinical trials for their new drug have only a 12% success rate. Even if a newly developed drug passes all required steps to bring it to market, pharmaceutical companies face heavy competition with each other.

To create efficiencies in the drug development process to lower costs and increase the likelihood that a drug passes clinical trials, pharmaceutical companies can benefit greatly from collaborating with each other and other technology organizations. An example of this collaboration within the pharmaceutical industry was the agreement between Pfizer and BioNTech to begin developing a vaccine for COVID-19. One year later, the BioNTech, Pfizer vaccine was approved for use worldwide.

Part of this collaboration requires the need to safely share intellectual property and research findings with each other. Their data must be protected from unintended disclosure by competitors and adversaries to avoid reputation damage, profit loss, and brand impact.

Although the rise of quantum computing undoubtedly benefits pharmaceutical companies regarding drug development, it also brings about challenges for them about collaborating with each other and sharing their intellectual property in a secure manner.

If an adversary with access to a quantum computer can break the encryption algorithms that are used to protect shared information, they can publicly expose a pharmaceutical company's research findings that can result in a significant advantage for their competitors to release a similar drug.

By taking advantage of the quantum-safe capabilities with IBM z16, these organizations can use the benefits that quantum computers can provide in Research and Development while also ensuring that intellectual property that is shared between companies remains secure.

¹ See: [Protecting Intellectual Property Rights in the Pharmaceutical Industry](#)

Government bodies

Government bodies often partner with other government agencies and the private sector to create efficiencies in their operations. For example, information sharing programs are used that are dedicated to saving government resources through partnerships between various federal, state, and municipal government agencies. As part of these information sharing programs, the previously mentioned agencies are entitled to exchange taxpayer information with each other.

This example the need to facilitate the sharing of confidential information between partnering agencies. Although safeguards exist to protect the confidentiality of taxpayers' information, the threat of quantum computing presents challenges for maintaining this confidentiality in the future.

Government bodies greatly benefit from the capabilities that are provided with IBM z16 to enable secure information sharing with partners. By using quantum-safe hybrid key exchange schemes, government agencies can maintain the confidentiality of their citizens' information as it is shared to ensure that not even a quantum computer can intercept the information and break the encryption algorithms that are used to protect it.

Banking

In financial services, such as banking, a significant need exists to protect business-critical data in the face of quantum computing. Although many examples exist of data that requires protection in banking, a simple example to illustrate is in the case of credit card information.

Banks are required to comply with the Payment Card Industry Data Security Standard (PCI DSS) for protection of customer's sensitive payment card information. As a result, security protocols are in place to protect their sensitive data as it is transmitted between point-of-sale (POS) terminals and the bank. This process typically is done by encrypting the data that is in transit between the two parties.

PCI DSS implies is that both parties must have a shared symmetric key that is used to encrypt the customer data at the POS and then decrypt it when in the hands of the bank. Even when quantum-safe symmetric key algorithms are used, such as AES (assuming 256-bit keys) for this encryption and decryption, the problem is that the shared keys are typically exchanged through classical public key cryptography schemes alone that are not quantum-safe. For example, they might use ECDH as their key agreement protocol to derive their symmetric encryption key.

As a result, the protection of their customers' sensitive payment card information can potentially be exposed if a cybercriminal harvests the encrypted data now to decrypt in the future after they obtain access to a quantum computer of sufficient scale.

Therefore, banks and other organizations that deal with sensitive payment card information can benefit greatly by using the hybrid key exchange schemes that are available with IBM z16. By doing so, they securely derive a shared encryption key that cannot be derived in the face of high-powered quantum computers.

Automotive and aerospace

Similar to the pharmaceutical industry, automotive and aerospace companies must protect their intellectual property from unintended information disclosure from their competitors to avoid reputation damage, profit loss, and brand impact. They also must collaborate with Business Partners to develop the latest cutting-edge capabilities in their respective industries.

To enable this collaboration, they must share their intellectual property and proprietary research findings with each other in a way that is secure and cannot be exposed to bad actors and competitors. This sharing also is done by way of encrypting confidential data in transit by using mutually derived encryption keys.

Because these keys are shared between partnering organizations by using traditional public key cryptography alone, it can be concluded that quantum computers eventually can expose the organizations' confidential information that is shared between parties by breaking the traditional public key algorithms that are used today.

Therefore, the quantum-safe key exchange mechanisms that are available with IBM z16 can be used. As a result, automotive and aerospace companies can be assured that the intellectual property they are exchanging with partners is never exposed in the clear to avoid unintended information disclosure.

3.3 Use case: Message integrity and secure logging

This use case addresses the problem of ensuring the integrity of messages and logs in the presence of quantum computers and how capabilities that are provided with IBM z16 can solve these challenges.

Organizations that send messages and digital assets to other parties, such as legal documents, audit logs, financial statements, and historical records, traditionally ensured the integrity of their messages by using digital signatures.

By using digital signatures, organizations can ensure that the receiver of a message or document knows whether the message is genuine and untampered. This feature makes it possible to prevent legal and documentation fraud.

However, with the rise of quantum computing, adversaries with access to a quantum computer of sufficient scale can undetectably rewrite history and modify documents, messages, and logs, and claim that the tampered message was indeed the original message the organization sent.

This section addresses how IBM z16 capabilities can overcome this security challenge.

Although digital signatures can serve multiple purposes, the focus of this use case is on message integrity. Digital signatures can also help achieve identity authentication, or proof of authorship, as described in 3.4, "Proof of authorship" on page 42.

3.3.1 Problem statement

In the past, organizations relied on digital signatures to ensure the integrity of messages, digital documents, and logs used for auditing purposes. Traditionally, when an organization sent a digitally signed message or document to another party, the other party verified the digital signature to ensure that the document or message was genuine and was not modified by an adversary. By using digital signatures, organizations avoided advanced legal and documentation fraud.

Digital signatures rely on public key cryptography. ECDSA is one example of a popular cryptographic algorithm that is used for digital signatures.

For an organization to send a message or document to another party and ensure it was not tampered with in-transit, they digitally sign the document by using ECDSA, for example. The process begins with the organization generating an ECC key pair (consisting of a private and public key). They then use the ECDSA signing algorithm to generate a digital signature.

As part of the algorithm's signing process, a cryptographic hash of the message, document, or log is first calculated by using a hash algorithm, such as SHA-256. Because the hash generation is a one-way function, meaning the hash value is unique to the exact contents of the message or document, any effort to modify the message or document results in a different, inconsistent hash value.

Following the hash value generation, it is signed by using the organization's private key, to which only they have access. The signed hash is then appended to the document or message and is sent to the party it was intended for, along with the organization's public key.

The retrieving party can verify the integrity of the message or document by using ECDSA and the public key that was shared:

1. The party generates their own hash of the document or message by using the same hash function that was used to sign it.
2. They then use the shared public key to verify the signed hash that was appended to the document or message.
3. As part of the ECDSA verification process, the newly computed hash value is compared with the decrypted hash value that was appended to the document.

If the two hashes match, the party can be assured that the message was not tampered with in-transit and the contents of the message or document are exactly what the original organization sent.

If the hashes do not match, the receiving party can conclude that the message was tampered with because the hash that they generated differs only from the appended hash if the message's contents was changed in-transit.

When digital signatures are used, the receiving party can reliably determine the integrity of the message because they assume that only the original organization includes the mathematically related private key that was used to sign the hash and nobody else. This assumption can be made because of the mathematical complexity of the elliptic-curve discrete logarithm problem.

The only way for an adversary to obtain the original organization's private key is to derive it from the associated public key by solving this mathematical problem. However, it is not feasible for a conventional computer to solve this problem because it likely takes millions of years. As a result, it traditionally was accepted that the appended signed hash is the hash value that was generated from the original message or document. Therefore, the integrity can be determined by comparing the receiver's hash output with the appended hash value.

With the rise of quantum computing, eventually it will be possible for a quantum computer of sufficient scale to solve this once considered complex problem in only a matter of hours by using Shor's algorithm.

An adversary with access to a quantum computer might take an entity's public key and derive the associated private key. After it is in the hands of an adversary, they can alter the contents of the message or document undetectably.

When the organization sends the message to the intended party, the adversary can run a “man in the middle” attack to intercept the original message, modify its contents, re-create a new hash value, and then, sign this new hash by using the organization’s private key. This newly signed message is then forwarded to the intended party. The party has no way of ensuring its integrity because the hash value that was generated is identical to the newly appended hash value.

This ability to undetectably modify messages, documents, and logs by using quantum computers can result in disastrous consequences, especially when considering the various regulations, such as eIDAS (in the EU), and UETA and E-SIGN (in the US) that allows digital signatures to have equal legal status to traditional “wet” signatures. In addition, adversaries might tamper with potentially life-saving messages that are used in the automobile industry and messages that are used for international government communication.

3.3.2 Solving the integrity challenge with IBM z16 capabilities

The challenge of ensuring message, document, and log integrity in the face of quantum computing can be alleviated by using the dual digital signature schemes that are made possible with IBM z16. For more information about the procedures that are used to enable these dual digital signature schemes, see “Quantum-safe digital signatures” on page 107.

By using this IBM z16 capability, organizations can ensure message integrity by digitally signing their messages and documents by using a classical cryptographic algorithm and a quantum-safe cryptographic algorithm.

For example, a dual digital signature can be generated by using a classical cryptographic algorithm, such as ECDSA, with a quantum-safe cryptographic algorithm, such as CRYSTALS-Dilithium. IBM z16 enables this through enhancements in the Crypto Express8S (CEX8S) features to provide quantum-safe algorithm APIs.

As in the past, it is important to continue the use of a classical cryptographic signature algorithm, such as ECDSA, to comply with the various standards and compliance requirements mandating the use of approved signing algorithms. However, with the use of a classical cryptographic algorithm for digital signatures, it is also crucial to begin safeguarding information with a quantum-safe cryptographic scheme to ensure that message integrity is maintained in the face of CRQC attacks.

To ensure that message integrity is maintained in the future, an organization can use IBM z16 to digitally sign their out-bound messages and documents by using two digital signatures. This process is explained next (for more information, see “Quantum-safe digital signatures” on page 107).

An organization that wants to ensure the integrity of its messages begins by generating a hash of its message by using a cryptographic hash algorithm, such as SHA-256.

Then, the organization generates two key pairs. For example, they might generate an ECC public key pair and a quantum-safe CRYSTALS-Dilithium key pair (ICSF supports the CRYSTALS-Dilithium signature algorithm on the CCA and PKCS#11 APIs for IBM z16).

The organization then signs this hash with ECDSA by using their ECC private key, which results in an ECC signature. With generating that ECC signature, the organization also signs the same hash by using their CRYSTALS-Dilithium private key to generate a quantum-safe signature. The result is that two signatures exist for the single hash of the message, and both signatures are appended to the message for verification purposes.

Anyone who wants to verify that the message was not modified or tampered with in-transit uses the CRYSTALS-Dilithium public key to verify the Dilithium signature and the ECC public key to verify the ECC signature. As part of the verification process, the receiving party generates the hash value of the message and passes the hash value and the suitable digital signature to the signature verification function for each signature algorithm. If the ECC signature verifies and the CRYSTALS-Dilithium signature verifies, the party can be assured that the message was not tampered with by a bad actor, and thus, message integrity is maintained.

As shown in Figure 3-4, success indicates message integrity and authorship by the owner of the public key.

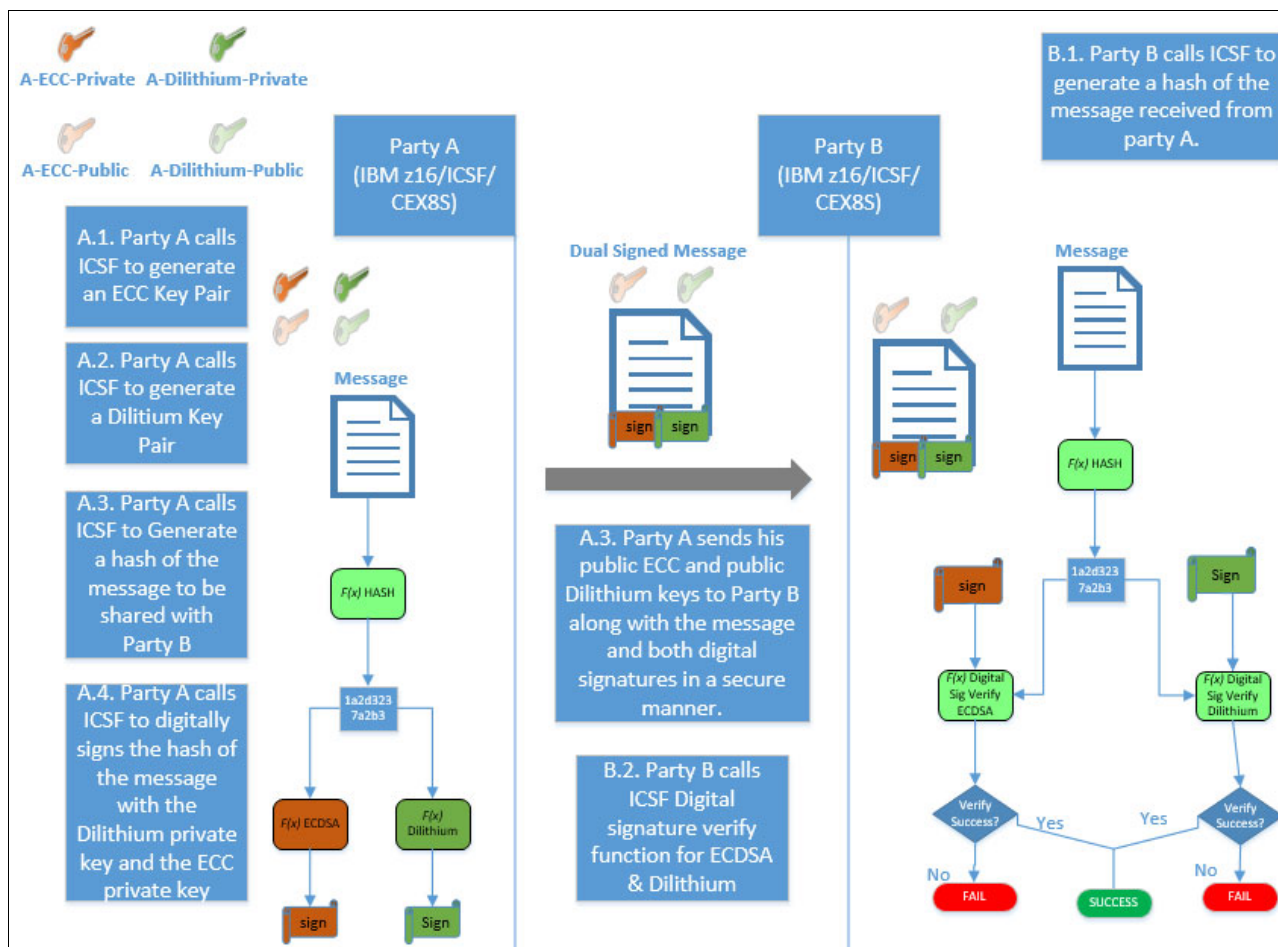


Figure 3-4 Validating the authenticity (proof of authorship) and integrity of a message

This dual digital signature scheme that is enabled with IBM z16 solves the challenge of ensuring message integrity, even if an adversary can access a quantum computer that can run Shor's algorithm.

Suppose that the adversary ran a man-in-the-middle attack to intercept the original message, modify its contents and then, re-create a new hash value. Although they can sign the new hash by using the organization's ECC private key that they derived by using Shor's algorithm, they have no way of signing the same hash by using the organization's CRYSTALS-Dilithium private key because it is quantum-safe.

A single ECC signature is of no value because the integrity verification works only if a valid ECC signature and a valid Dilithium signature with the message are available.

3.3.3 Industry applications

This section describes the wide range of applications that quantum-safe digital signatures have across different industries. Also discussed is how financial services organizations, automotive companies, software vendors, and even law firms might all benefit from the dual digital signature schemes that are enabled with IBM z16 to ensure that their communications and data were not tampered with or targeted by adversaries with access to quantum computers.

Banking

In the banking industry, digital signatures prove to be a vital necessity in securing financial transactions and messages between banks. Society for Worldwide Interbank Financial Telecommunication (SWIFT) was created in the 1970s to enable banks across the world to share information about financial transactions with each other. These high-value electronic transactions and messages can be shared between banks over the SWIFT network, which relies on public key infrastructure to digitally sign and encrypt messages.

The growing presence of quantum computing throughout the world threatens the long-term security of these types of banking transactions. Relying on traditional public key cryptography alone for securing these interbank transactions poses a vulnerability in message integrity because adversaries with access to quantum computers can inevitably forge transactions and messages.

The banking industry might also be one of the first targets of CRQC attacks because of the profit potential for cybercriminals. Adopting quantum-safe dual digital schemes in the banking industry is a must to secure interbank financial transactions in the future.

Automotive industry

In the automotive industry, manufacturers are constantly innovating new ways of improving driver safety. One of these innovations is the rise of vehicle-to-vehicle (V2V) communication that aims to make driving safer by allowing vehicles to communicate with each other to prevent crashes, traffic, and so on.

Quantum computing poses security challenges for this V2V communication in which messages between vehicles might be tampered with by bad actors. Messages that are transmitted between vehicles that are digitally signed by using traditional public key cryptography alone, such as RSA or ECDSA, no longer guarantee the integrity of these V2V messages when quantum computers of sufficient scale are available to bad actors.

Adversaries might manipulate messages to create life-threatening situations on highways and in busy cities. By taking advantage of the dual digital signing schemes that are available with IBM z16, vehicle manufacturers can use quantum-safe digital signing to thwart message tampering attacks and make driving safer.

Software vendors

In software development, vendors aim to secure software distribution by using digital signatures that are based on public key cryptography.

For example, updates to a software release are often digitally signed by using RSA or ECDSA encryption algorithms to ensure that customers can verify whether the software was tampered with before installation. Oftentimes, these software updates require automatic digital signature verification before installing the update.

The traditional algorithms that are used today for digitally signing software were reliable in ensuring its integrity; however, with the rise of quantum computing, integrity is no longer guaranteed because bad actors can tamper with the software undetectably.

This tampering can result in a customer installing malware on their systems. Therefore, it is critical that software vendors implement quantum-safe dual digital signature schemes in their products.

Legal industry

In the legal industry, regulations, such as eIDAS (in the EU) and UETA and E-SIGN (in the US) allow digital signatures to have equal legal status to traditional “wet” signatures.

Historically, confidential legal documents that use digital signature capabilities were not forged because the integrity of these documents was ensured through verification of the digital signatures by the receiving party.

However, quantum computers that can quickly derive the private keys serving as the underpinnings of these digital signatures eventually will make it possible to manipulate and tamper with legal documents by forging digital signatures.

To avoid advanced legal fraud and impersonation attacks in this era where digital signatures serve as legal evidence, it is critical that law firms begin safeguarding their legal documents and communications with quantum-safe dual digital signature schemes that are available with IBM z16.

3.4 Proof of authorship

Organizations that made their valuable assets digitally accessible, such as legal documents, financial statements, historical records, and license code, often ensured nonrepudiation such that the public can trace back these digital assets to the original creator.

Proof of authorship was achieved by using digital signatures where anyone can verify the authenticity of a digitally signed document or digital asset. Digital signatures also make it impossible for any unknown entity to disseminate information or assets to the public and claim it came from someone else, which ensures responsibility for the distribution of digital information.

In the legal industry, various regulations are in place that allow digital signatures to have equal legal status to traditional “wet” signatures. Because legal documents might feature long lifetimes, the signatures on them might need to be secure for decades.

With the rise of quantum computing, adversaries with access to a quantum computer of sufficient scale can manipulate legal history by forging digital signatures. As a result, the legal underpinnings of digitalization are now vulnerable.

This use case illustrates how organizations can avoid advanced legal fraud and impersonation attacks by using the quantum-safe capabilities that are available on IBM z16.

3.4.1 Problem statement

Organizations traditionally made their digital assets public while ensuring proof of authorship and nonrepudiation. Anyone accessing or viewing these digital assets can verify exactly from who it came, which is made possible by using digital signatures.

Nonrepudiation and proof of authorship are ensured because these digital signatures are generated by using a private key that is only known by the signer. As a result, the signer has no means of repudiating their signature that is added to the document.

If a dispute occurs, proof of authorship enables the document's authorship to be supported by evidence, being the holder of the private key.

Digital signatures

Digital signatures are made possible with the use of public key cryptography. One example of a popular cryptographic algorithm for digital signatures is ECDSA. Organizations that wanted to digitally sign a document so that the public can trust that it came from them begins by generating an ECC key pair that consists of a private and public key.

They then use the ECDSA signing algorithm to digitally sign their document. The algorithm works by first calculating a cryptographic hash of the document by using a cryptographic hash algorithm, such as SHA-256. This hash is unique to the exact contents of the document.

If the document was modified, the resulting hash output is different. As part of the signing algorithm, the hash value then is signed by using the signer's private key, which only they can access. The signed hash is appended to the document and made publicly available along with the signer's public key.

Now that the document is digitally signed, anyone who wants to access the document can verify its authenticity by using ECDSA and the public key. The receiver uses the public key that they received to verify the signed hash that is appended to the document.

They also generate a hash output of the same document by using the same hash function that was used to sign the document. The algorithm then compares the hash value that the receiver computed with the decrypted hash value that was appended to the document. If the two hashes match, the public key sender is verified as the true author of the document because it is assumed that only they have the mathematically related private key.

Elliptic-curve discrete logarithm problem

The strength of these digital signatures for proving authorship of a digital asset is a result of the mathematical complexity of the elliptic-curve discrete logarithm problem. The only way to derive the private key from the associated public key is to solve this mathematical problem, which is not feasible for conventional computers because it likely takes millions of years to solve the elliptic-curve discrete logarithm problem.

Therefore, it was always assumed that the private key holder is the author of the digitally signed document, which is how proof of authorship can be ensured. As a result, public key cryptography alone was considered secure for digital signatures.

With the rise of quantum computing, it eventually will be possible for a quantum computer of sufficient scale to solve this once considered complex problem in only a matter of hours by using Shor's algorithm. An adversary with access to a quantum computer might take an entity's public key and derive the associated private key, which can have disastrous consequences.

By using that entity's private key, the adversary can forge their digital signature to manipulate legal history and claim that the digital assets they create were authored by the entity whose private key they possess.

Making matters worse, many legal documents (and the signatures on them) are in public records; therefore, an adversary can easily obtain them and attack the cryptography with a quantum computer. No "hacking" is necessary to get to the data to be attacked. Documents, messages, certificates, software, and transactions all can be forged. Therefore, an identity over the internet is no longer guaranteed.

3.4.2 Solving this challenge with IBM z16 capabilities

Capabilities that are provided by IBM z16 allow organizations to solve this challenge that is faced today with the threat of quantum computing by using dual digital signature schemes and quantum-safe key generation. For more information about enabling these dual digital signature schemes, see "Quantum-safe digital signatures" on page 107.

With IBM z16, it is possible for organizations to digitally sign their valuable assets by using a classical cryptographic algorithm and a quantum-safe cryptographic algorithm. The ability to use a quantum-safe cryptographic algorithm, such as CRYSTALS-Dilithium, with a classical cryptographic algorithm, such as ECDSA, is supported by the quantum-safe algorithm APIs within the new Crypto Express cards (CEX8S) that was provided with IBM z16.

The value in the use of this dual digital signature scheme is two-fold: First, as in the past, it is important to use a classical cryptographic signature algorithm, such as ECDSA, because various standards and compliance requirements exist that require standards-approved signing algorithms.

Uncertainty also exists about how those standards might change in the future with the rise of quantum computing. Although newly developed algorithms might be considered "quantum-safe," it is never guaranteed that these algorithms are not to be found insecure.

Therefore, as a minimum security measure, it is beneficial to continue the use of these classical signature schemes to thwart attacks from conventional computers. Also, to begin safeguarding valuable information in the future, even in the face of high-powered quantum computers, it is important to buttress this protection with a known quantum-safe cryptographic signature scheme with IBM z16.

To maintain proof of authorship and nonrepudiation for an organization's digital assets, they use IBM z16 to create two digital signatures that public entities can verify (see Figure 3-4 on page 40):

1. A hash of their document is generated by using a cryptographic hash algorithm, such as SHA-256.
2. The organization generates two key pairs. For example, they might generate an ECC public key pair and a CRYSTALS-Dilithium key pair (ICSF supports the CRYSTALS-Dilithium signature algorithm on the CCA and PKCS#11 APIs for IBM z16).
3. The organization signs this hash with ECDSA; for example, by using their ECC private key, which results in an ECC signature. Along with generating that ECC signature, the organization also signs the same hash by using their CRYSTALS-Dilithium private key to generate a quantum-safe signature.

This process results in having two signatures for the single hash of the message, and both signatures are appended to the digital document for verification.

Anyone who wants to verify that this organization authored the document uses the CRYSTALS-Dilithium public key to verify the Dilithium signature and the ECC public key to verify the ECC signature. If both signatures are successfully verified, the verifying party can be assured that the document was authored by the organization.

The threat that is created by quantum computers of sufficient scale to forge digital signatures is negated because both signatures must verify.

Even if an adversary with access to a quantum computer can run Shor's algorithm to derive the ECC private key by using the related public key, they cannot forge the organization's signature because they cannot derive their CRYSTALS-Dilithium private key.

Suppose a cybercriminal with access to a quantum computer can create a fake document and sign it with the derived ECC private key. The ECC signature is created, but the adversary does not have the CRYSTALS-Dilithium private key to create a Dilithium signature.

A single ECC signature is of no value because the verification works only if a valid ECC signature and Dilithium signature exists with the document.

For more information, see "Quantum-safe digital signatures" on page 107.



Getting ready for quantum-safe cryptography

In this chapter, we introduce the cryptographic components that are available on the IBM Z platform.

We also describe an approach to help discover and classify data, establish a cryptographic inventory by using various tools, and adopt quantum-safe cryptography on IBM Z.

Discussions about best practices, mitigation options, and encryption key management tools are also included.

This chapter includes the following topics:

- ▶ 4.1, “IBM Z cryptographic components overview” on page 48
- ▶ 4.2, “Steps towards quantum protection” on page 56
- ▶ 4.3, “Best practices, mitigation options, and tools” on page 65

4.1 IBM Z cryptographic components overview

The cryptographic stack on the IBM Z platform consists of many different hardware and software components that provide unique capabilities to aid in securing your environment. In this section, the components that are available for quantum-safe cryptography are briefly described. We also review the required levels of hardware and software components to implement quantum-safe cryptography in your IBM Z environment.

4.1.1 IBM Z cryptographic hardware components

On the hardware side, quantum-safe cryptography is supported by the Crypto Express hardware security module (HSM) and the Central Processor Assist for Cryptographic Functions (CPACF).

Cryptographic functions can be categorized in the following groups from an application program perspective:

- ▶ Symmetric cryptographic functions and hashing functions are provided by CPACF or Crypto Express features
- ▶ Asymmetric cryptographic functions and digital signatures are provided by Crypto Express features, while some are also provided by CPACF

For more information about the different types of cryptography, see 1.2.1, “Cryptography overview” on page 5.

CPACF

Each processor unit (PU) chip in the IBM Z platform has an independent cryptographic engine (known as a cryptographic assist). CPACF is a high performance, low-latency coprocessor that performs symmetric key encryption operations and calculates message digests (hashes) in hardware.

The following algorithms are supported:

- ▶ Advanced Encryption Standard (AES) for 128-bit, 192-bit, and 256-bit keys
- ▶ Data Encryption Standard (DES) and Triple Data Encryption Standard (TDES)
- ▶ Hashing algorithms:
 - Secure Hash Algorithm (SHA)-1
 - SHA-2
 - SHA-3
 - SHAKE

CPACF supports Elliptic Curve Cryptography (ECC) clear key, which improves the performance of Elliptic Curve (EC) algorithms. The following algorithms are also supported:

- ▶ EdDSA (Ed448 and Ed25519)
- ▶ ECDSA (P-256, P-384, and P-521)
- ▶ ECDH (P-256, P-384, P521, X25519, and X448)
- ▶ Support for protected key¹ signature creation

z/OS Integrated Cryptographic Services Facility (ICSF) uses CPACF to accelerate cryptographic functions. For ICSF to use these functions, Feature Code (FC) 3863 must be enabled. This FC is not enabled by default.

¹ A protected key is a data-encrypting key that is encrypted by a CPACF wrapping key and used within the IBM Z platform.

IBM z16 includes counters for CPACF to track cryptographic algorithms, bit lengths, and key security. The CPACF counters provide evidence for compliance (which cryptography is used), performance (frequency of cryptography use), and configuration (proof of change).

For more information, see “IBM ICSF cryptographic usage tracking” on page 59, and “Formatting cryptographic usage statistics records” on page 75.

Crypto Express

Each Crypto Express HSM contains cryptographic engines that can be configured as a Common Cryptographic Architecture (CCA) cryptographic coprocessor (CEX_{*n*}C)², as an Enterprise Public Key Cryptography Standard #11 (PKCS #11) cryptographic coprocessor (CEX_{*n*}P), or as an accelerator (CEX_{*n*}A) for public key and private key cryptographic operations that are used with SSL/TLS processing.

Crypto Express coprocessors enable secure key generation and operations under the direction of ICSF. It is recommended that at least two of each type (CCA coprocessor or Enterprise PKCS#11 coprocessor or accelerator) be configured for redundancy.

If one coprocessor must be taken offline, the second coprocessor that is loaded with same master keys³ can handle new requests.

On IBM z15 and IBM z16, up to 60 Crypto Express coprocessors can be configured, each supporting up to 85 cryptographic domains⁴. Each domain is protected by a master key, which prevents access across domains and effectively separates the contained keys.

Quantum-safe algorithms are supported by the Crypto Express7S and Crypto Express8S coprocessors. For more information about the supported algorithms for each coprocessor type, see 4.1.3, “Minimum hardware and software for quantum-safe cryptography support” on page 55.

Secure boot technology

In addition to the quantum-safe cryptography support in the CPACF and Crypto Express features, IBM z16 secure boot technology uses quantum-safe and classical digital signatures to perform a hardware-protected verification of the Initial Machine Load (IML) firmware components. This firmware integrity protection is anchored in a hardware-based Root of Trust (RoT) to ensure that the system starts securely by keeping unauthorized firmware (or malware) from taking over during start.

Trusted Key Entry

As an option, a Trusted Key Entry (TKE) Workstation can be used to securely manage and load cryptographic keys. Keys can be loaded remotely for multiple Crypto Express HSMs. A TKE is required for Crypto Express coprocessors in Enterprise PKCS#11 (EP11) mode. The TKE feature contains a combination of hardware, firmware, and software. An optional smart card reader can be added to the TKE Workstation.

With z16 and TKE 10.0, quantum-safe encryption algorithms are now used for key exchange. For more information, see “Trusted Key Entry” on page 69.

² *n* is a 7 or 8, which represents a Crypto Express7S feature or Crypto Express8S feature, respectively.

³ A master key is a special key-encrypting key (KEK) that is in a tamper-responding, Crypto Express adapter. A master key sits at the top level of a KEK hierarchy.

⁴ A domain acts as an independent cryptographic device with its own master key. Domains in the same Crypto Express are isolated. Domains are assigned to IBM Z logical partitions (LPARs).

Figure 4-1 shows the hardware components for implementing quantum-safe cryptography in an IBM Z environment.

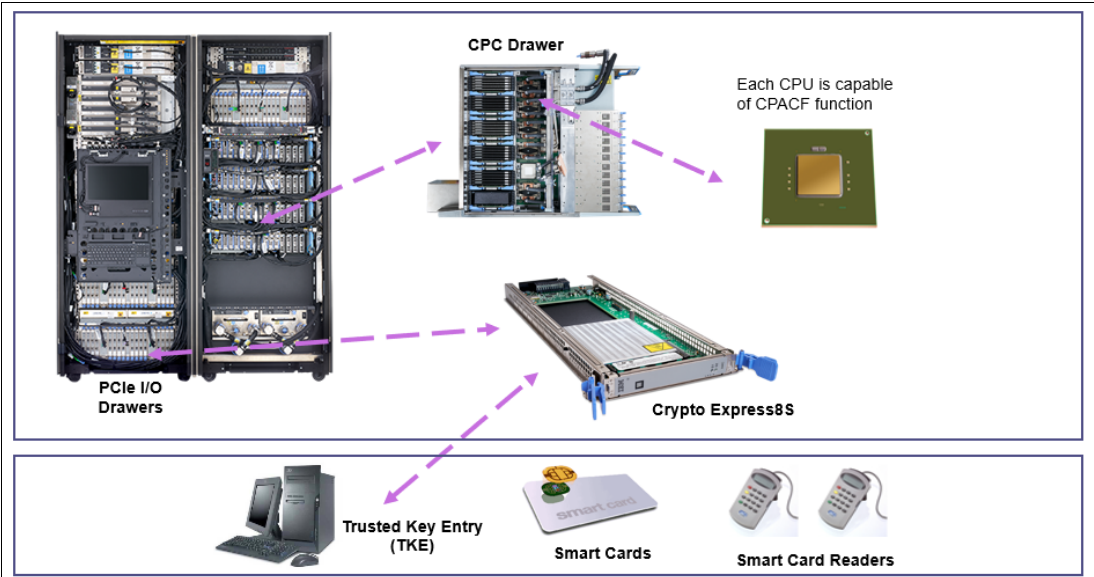


Figure 4-1 IBM Z cryptographic hardware components

For more information about the cryptographic hardware components, see *IBM z16 (3931) Technical Guide*, [SG24-8951](#).

Crypto Express features

Crypto Express8S and Crypto Express7S features provide quantum-safe RoT and quantum-safe cryptographic APIs for application program use (see Table 4-1).

Table 4-1 Crypto Express features for quantum-safe cryptography

Feature	Description
Crypto Express8S Dual-HSM (FC 0908)	This feature contains two IBM 4770 PCIe cryptographic coprocessors, which can be independently defined as a coprocessor or an accelerator. Supported on IBM z16.
Crypto Express8S Single-HSM (FC 0909)	This feature contains one IBM 4770 PCIe cryptographic coprocessor, which can be defined as a coprocessor an accelerator. Supported on IBM z16.
Crypto Express7S Dual-HSM (FC 0898)	This feature contains two IBM 4769 PCIe cryptographic coprocessors, which can be independently defined as a coprocessor or an accelerator. Supported on IBM z15 and IBM z16.
Crypto Express7S Single-HSM FC 0899)	This feature contains one IBM 4769 PCIe cryptographic coprocessor, which can be defined as a coprocessor or an accelerator. Supported on IBM z15 and IBM z16

Crypto Express8S

When the Crypto Express8S adapters are configured in CCA or EP11 mode, the following support for quantum-safe symmetric algorithms (AES, CMAC, and HMAC), hashing algorithms (SHA-2, SHA-3), and digital signature algorithms are enabled by using:

- ▶ CRYSTALS-Dilithium 6,5 (Round 2)
- ▶ CRYSTALS-Dilithium 8,7 (Round 2)

- ▶ CRYSTALS-Dilithium 6,5 (Round 3)
- ▶ CRYSTALS-Dilithium 8,7 (Round 3)

Also, the following quantum-safe key encapsulation mechanisms (KEM) are supported:

- ▶ CRYSTALS-Kyber 1024 (Round 2) is implemented as part of a hybrid key exchange mechanism
- ▶ Hybrid key agreement scheme combining Elliptic Curve Diffie-Hellman (ECDH) and CRYSTALS-Kyber

Crypto Express7S

When the Crypto Express7S adapters are configured in CCA or EP11 mode, the support for quantum-safe symmetric algorithms (AES, CMAC, and HMAC), hashing algorithms (SHA-2, SHA-3), and digital signature algorithms are enabled through CRYSTALS-Dilithium 6,5 (Round 2).

For more information about quantum-safe algorithms, see “New algorithms to counter CRQC attacks” on page 11.

Hybrid key exchange mechanism

The use of secure keys⁵ and protected keys in the IBM Z encryption process ensure that data-encrypting keys are not visible to unauthorized callers (see Figure 4-2).

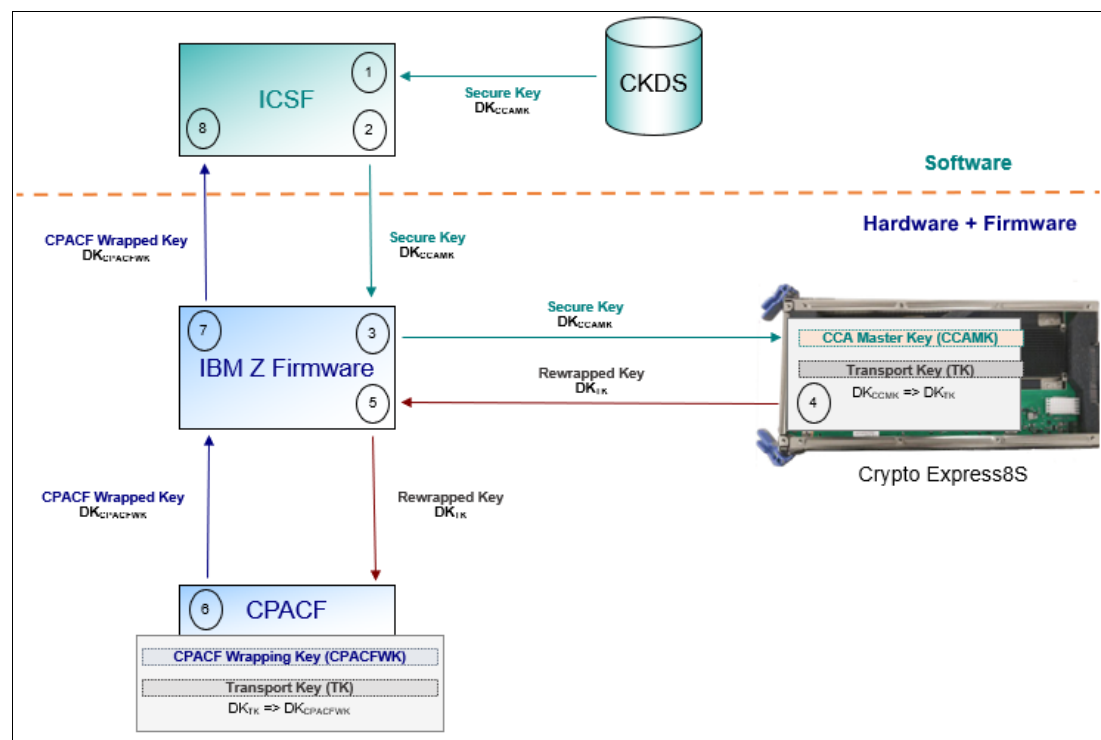


Figure 4-2 IBM z16 and Crypto Express8S process to create protected keys

When first created, the data-encrypting key is wrapped (encrypted) as a secure key by ICSF by using a master key, which is stored in the hardware security module (HSM) of an assigned Crypto Express adapter when configured in CCA mode.

⁵ A secure key is a data-encrypting key that is encrypted by a master key or key-encrypting key and never appears in clear text that is outside of a secure environment, such as a tamper-responding HSM, or IBM Z firmware. Secure keys can be stored in an ICSF key data set or returned to the ICSF caller.

In IBM z16 firmware, a hybrid key exchange mechanism that includes CRYSTALS-Kyber, CRYSTALS-Dilithium, and ECDH is used to securely negotiate a shared transport key (AES 256-bit key) between the Crypto Express8S HSM and the CPACF. The shared transport key is used to protect data-encrypting keys that are sent from the Crypto Express8S HSM to the CPACF by way of IBM z16 firmware as part of the runtime process to create protected keys.

A CPACF wrapping key is used to rewrap a data-encrypting key as a protected key. The protected key is sent to ICSF for use by authorized callers. The CPACF wrapping key is in a protected area of the hardware system area (HSA) of the IBM Z platform, which is not accessible to the operating system, applications, or users.

The following process is used to create a protected key from a secure key, as shown in Figure 4-2 on page 51:

1. ICSF retrieves the data-encrypting key (DK) that is stored in the CKDS as a secure key (encrypted by using a master key [CCAMK]).
2. ICSF starts the process by sending the secure key (DK_{CCAMK}) to IBM Z firmware.
3. IBM Z firmware sends the secure key to the suitable domain in the Crypto Express8S HSM.
4. Crypto Express8S HSM decrypts the secure key by using the master key and rewraps the data-encryption key by using a transport key (TK). The transport key is derived from two independent contributions of entropy as part of the hybrid key exchange mechanism:
 - a. The ECDH calculation of the “Z” shared secret⁶, by using the private key of the IBM Z firmware and the public key of the Crypto Express8S HSM that is in the CPACF, and the corresponding public and private keys that are in the Crypto Express8S HSM.
 - b. The random number that is generated in the Crypto Express8S HSM is sent encrypted under the CRYSTALS-Kyber public key to the CPACF, which is then signed by a CRYSTALS-Dilithium private signing key.
5. The rewrapped data-encrypting key (DK_{TK}) is sent back to IBM Z firmware.
6. IBM Z firmware starts CPACF to unwrap and rewrap the data-encrypting key by using a CPACF wrapping-key (WK) to create a protected key (DK_{CPCFWK}).
7. IBM Z firmware returns the protected key (DK_{CPCFWK}) to ICSF.
8. ICSF caches the protected key in its address space and optionally returns the protected key to the authorized caller.

4.1.2 IBM Z cryptographic software components

z/OS ICSF provides the application programming interfaces (APIs) by which applications request cryptographic services, such as the following examples:

- ▶ Encryption and decryption
- ▶ Digital signature generation and verification
- ▶ Hash-based Message Authentication Code (HMAC) generation and verification
- ▶ Key and key pair generation
- ▶ Data hashing

ICSF callable services and programs can be used to generate, maintain, and manage operational keys (also known as *data-encrypting keys*), which are used in cryptographic operations.

⁶ Known only to the entities involved in a communication. Possession of that shared secret can be provided as proof of identity for authentication.

Figure 4-3 shows the ICSF architecture and its relationship with the IBM Z hardware and software components.

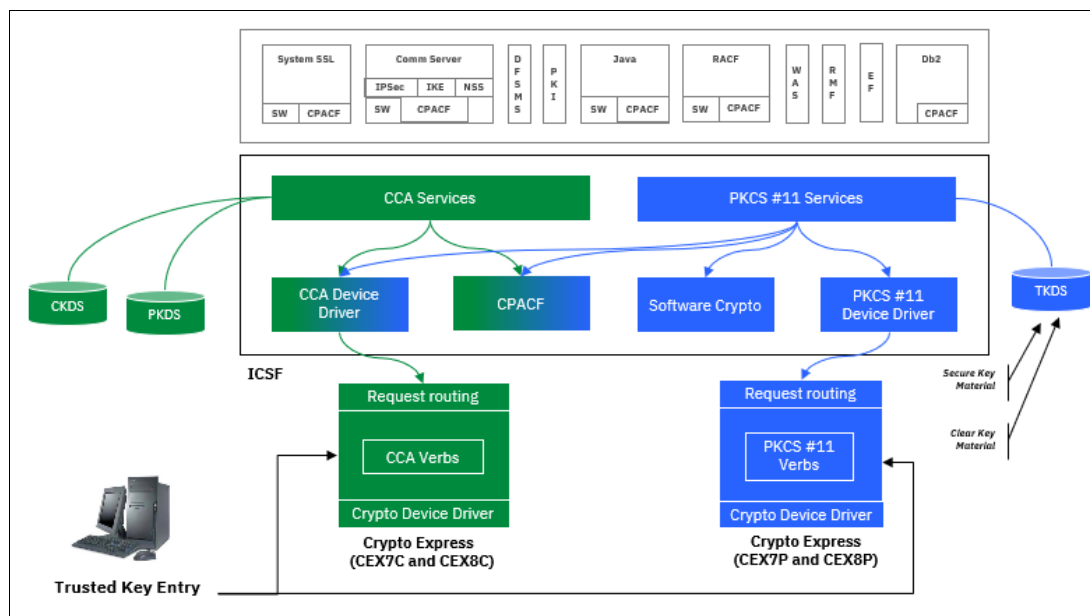


Figure 4-3 IBM Z software cryptographic components

ICSF supports two cryptographic architectures: CCA and Enterprise PKCS #11 (EP11). ICSF provides quantum-safe algorithms in both architectures. Software support for the algorithms is available by way of ICSF.

Hardware support for the algorithms is available through the Crypto Express7S or later. For more information about supported algorithms for each coprocessor type, see “Minimum hardware and software for quantum-safe cryptography support” on page 55.

ICSF provides callable services and utilities to generate and store cryptographic keys into ICSF Key Data Sets (KDS). Each KDS is a VSAM data set for persistent objects (such as keys and certificates) with programming interfaces for object management. Each record in the KDS contains the object and other information about the object.

The following types of ICSF Key data sets are available:

- ▶ CKDS: Cryptographic Key Data Set: Stores CCA Symmetric Keys such as AES, DES, and HMAC.
- ▶ PKDS: PKA Key Data Set: Stores CCA Asymmetric keys such RSA, ECC, and QSA.
- ▶ TKDS: Token Data set: Stores PKCS #11 Keys and Certificates.

If a PKDS is allocated and you want to store CRYSTALS-Dilithium or CRYSTALS-Kyber CCA key tokens, you must convert your PKDS over to KDSRL format. For more information, see “Converting your PKDS to KDSRL format” on page 99.

Master keys are used to protect sensitive operational keys that are used in your system. The number and type of master keys active in your system depend on your hardware configuration and application requirements:

- ▶ DES master key protects DES keys
- ▶ AES master key protects AES and HMAC keys
- ▶ RSA master key protects RSA keys
- ▶ ECC master key protects ECC, RSA, CRYSTALS-Dilithium, and CRYSTALS-Kyber keys

Master keys are stored within the secure hardware boundary of the Crypto Express HSM. The values of the master keys never appear in the clear outside the Crypto Express HSM.

For a master key to become active, the current active master key verification pattern (MKVP) in the Crypto Express HSM and the MKVP in the KDS header must match. When a new Crypto Express HSM is added to your environment, it must be loaded with the same master keys that were used to initialize the KDS.

You can verify the MKVPs in the Crypto Express HSM match the MKVP in the KDS by using the **D ICSF, MKVPS** command (see Example 4-1).

Example 4-1 Output from D ICSF, MKVPS command

```

D ICSF, MKVPS
CSFM668I 18.08.59 ICSF MKVPS 129
  CKDS  ICSF.CKDS.NEW
    AES MKVP Date=2022-03-25 00:25:40
    DES MKVP Date=2022-03-23 13:24:53
      ID      AES      DES
    KDSMKVPS .... 265995 0C3BE0
    SYSZ      7C00 265995 0C3BE0
    SYSZ      7C01 265995 0C3BE0
  PKDS  ICSF.PKDS.NEW
    ECC MKVP Date=2022-03-23 13:25:49
    RSA MKVP Date=2022-03-23 13:25:49
      ID      ECC      RSA
    KDSMKVPS .... 2ADB6C 4727DB
    SYSZ      7C00 2ADB6C 4727DB
    SYSZ      7C01 2ADB6C 4727DB
  No TKDS defined or no EP11 adapters online

```

For more information about the hardware ICSF supports, and master key types and how they are entered when ICSF first starts, see *z/OS Cryptographic Services ICSF Administrator's Guide*, SC14-7506.

4.1.3 Minimum hardware and software for quantum-safe cryptography support

Support for quantum-safe algorithms for CCA and PKCS #11 are provided in the IBM z15 and IBM z16 platforms. To ensure you can transition your applications to quantum-safe algorithms, verify that your environment meets the minimum hardware and software requirements for each algorithm.

Table 4-2 on page 55 lists the minimum hardware and software prerequisites to support quantum-safe cryptography on IBM z15 and IBM z16, based on algorithm strength and version.

Table 4-2 Minimum hardware and software prerequisites

Algorithm	Algorithm strength	Cryptographic hardware	ICSF required APARs	IBM Z platform ^a
CRYSTALS-Dilithium	CRYSTALS-Dilithium 6,5 Round 2	Crypto Express7S CCA coprocessor	HCR77D1 OA58880	IBM z15
		Crypto Express7S EP11 coprocessor	HCR77D1 OA58358	
	CRYSTALS-Dilithium 6,5 Round 3 CRYSTALS-Dilithium 8,7 Round 2 CRYSTALS-Dilithium 8,7 Round 3	Crypto Express8S CCA coprocessor	HCR77D1 OA61609	IBM z16
		Crypto Express8S EP11 coprocessor	HCR77D2 OA61609	
CRYSTALS-Kyber	CRYSTALS-Kyber 1024 Round 2	Crypto Express8S CCA coprocessor	HCR77D1 OA61609	IBM z16
		Crypto Express8S EP11 coprocessor	HCR77D2 OA61609	

a. Check with your IBM representative for IBM Z hardware driver levels that support quantum-safe cryptography on IBM z15 and IBM z16.

4.2 Steps towards quantum protection

As you begin to plan your transition to quantum-safe technology, several stages must be considered. These stages include discovering and classifying the data, creating a cryptographic inventory, considering cryptographic agility, and adopting quantum-safe cryptography. These topics are described in this section.

4.2.1 Discovering and classifying the data

It is important to classify and identify your most sensitive and valuable data. Classification of data is vital to help distinguish high-value information from information that does not have the same protection requirements. Protection requirement applies to data that belongs to your clients and the data you own.

This process also involves identifying the location of the data and understanding whether any compliance requirements or regulations are associated with the retention of that data.

Another essential consideration is identifying the internal data that your organization considers most valuable. It is important to create and manage a data inventory and define ownership of the data. Classifying data helps prioritize where to apply quantum-safe methods to protect the data. Some data must be protected because of regulations or standards that require compliance and those cases and the level of protection that is must be identified.

Some common types of data that must be protected include confidential business data, intellectual property data, and personally identifiable information (PII), such as social security numbers or drivers license numbers.

Confidential business data can include items, such as product release information, marketing strategies, financial reports, and communications with business partners.

Intellectual property can include design documents, research findings, trade secrets, and formulas. Each organization must identify the information that is most critical to protect.

Although not all data needs the same level of attention, prioritization is required in most cases during the quantum-safe cryptographic journey. It is important to know where your organization's most valuable or sensitive data resides.

Today, you might use encryption at the infrastructure level for data-in-flight or data-at-rest, and in your applications through middleware or custom application code.

Figure 4-4 shows where data encryption might be occurring today in your environment.

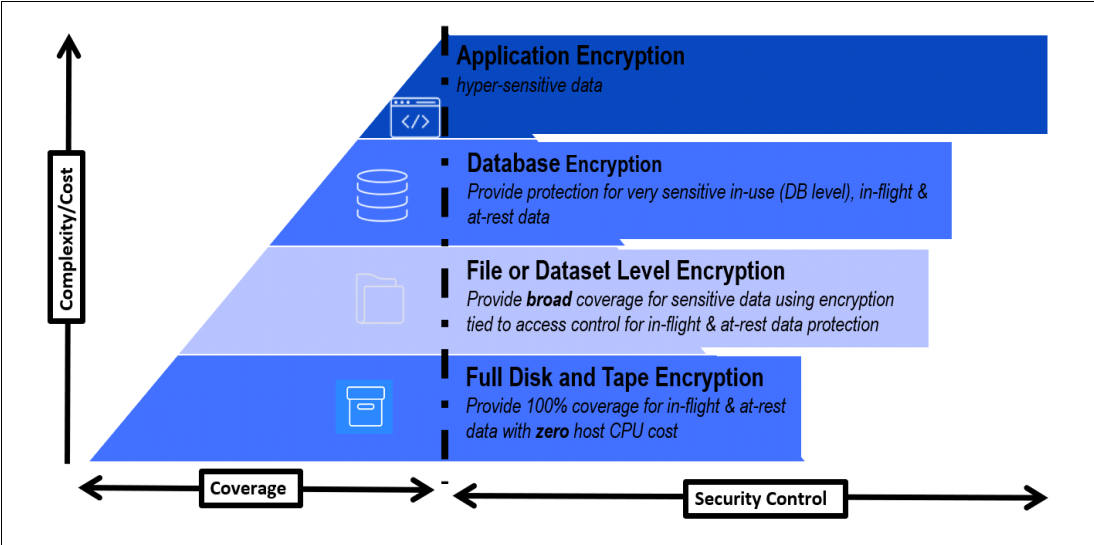


Figure 4-4 The encryption pyramid

IBM Z pervasive encryption⁷ can be used to provide quantum-safe protection for data at-rest with AES.

During the discovery step, you need help from the applications owners to identify the data they are processing in their applications. You also need the help of your risk and compliance team because they might already have a mapping of sensitive information and its location. If not, now is the time to collect such information and define ownership and location of all sensitive data.

After the ownership of the data and its sensitivity is established, it is key to prioritize the analysis of the applications and assets if encryption is used and if it is used, which cryptographic algorithm is being used. Based on this priority list, the application can enter the cryptographic inventory phase.

A sample application data asset inventory is shown in Figure 4-5.

Data Type/Asset	Application	Owner	Sensitivity	Priority
Data_1	Application_1, Application_3	Owner_1	High	1
Data_2	Application_2	Owner_2	Low	3
Data_3	Application_4, Application_5	Owner_1	High	2

Figure 4-5 Sample data inventory sheet

⁷ For more information, see [Getting Started with z/OS Data Set Encryption](#) and [Getting Started with Linux on Z Encryption for Data At-Rest](#).

4.2.2 Establishing a cryptographic inventory

Another vital stage is the creation of a cryptographic inventory, which is an important security artifact. A cryptographic inventory helps document the cryptographic algorithms that are used and why they are used.

For example, if the cryptography is used to digitally sign documents, the cryptographic inventory indicates specific information, such as the name of the signing application, which cryptographic algorithms are used, what are the lengths of the cryptographic keys that are used, and the details of the crypto algorithm provider.

It is important to identify how the documents are signed to determine which mitigation steps are required. Therefore, creating a repository that shows the cryptographic algorithms that are in use within the organization is important.

Also, consider areas where cryptography can be hidden from obvious view. Examples include configuration options that determine the cryptography in use (such as TLS configurations) and key containers (such as certificates).

If a vendor developed the component that uses cryptography, it is necessary to discuss this topic with that vendor to understand the cryptography that is used and the vendor's plans for adopting quantum-safe technology. After you have this type of information, you must determine whether the current cryptographic protection is sufficient, or if a mitigation action is required.

It also is important that you understand which algorithms are not considered quantum-safe (see 1.4, "Cryptographic vulnerabilities possible with quantum computers" on page 9).

A cryptographic inventory includes many items, such as the following examples:

- ▶ Component or application under evaluation
- ▶ Function or feature that uses crypto
- ▶ Person responsible (Who owns or uses the component?)
- ▶ Symmetric algorithms, function, and key size
- ▶ Asymmetric algorithms, function, and key size
- ▶ Hash algorithms and digest size
- ▶ Crypto algorithm implementation (hardware and software)
- ▶ Crypto provider (HSM and library)
- ▶ Crypto vendor (IBM or open-source)
- ▶ Interoperability with business or crypto partners
- ▶ Key provisioning and storage

The analysis is performed based on the priority list that is established when the discovering and classifying the data step is done (see Figure 4-5 on page 57). Each type of data and application must be assessed to identify the cryptographic algorithm in use. Encryption can be carried out at the infrastructure or at the application level.

Application owners should know whether and what encryption algorithm is used. If not, several tools can be used to assist during the cryptographic inventory step, including the following examples:

- ▶ IBM z/OS Integrated Cryptographic Service Facility (ICSF)
- ▶ IBM Application Discovery and Delivery Intelligence (ADDI)
- ▶ IBM Crypto Analytics Tool (CAT)
- ▶ IBM z/OS Encryption Readiness Technology (zERT)

All information that is captured must be recorded and stored in a safe place. A sample cryptographic inventory sheet (see Figure 4-8 on page 64).

IBM ICSF cryptographic usage tracking

ICSF cryptographic usage tracking with ICSF HCR77C1 (or later) supports data collection (in SMF records) for Crypto Express coprocessors, ICSF callable services, and cryptographic algorithm. The use of the SMF records that are created by the usage tracking provides the following identification information:

- ▶ All the jobs (or tasks) that use ICSF cryptographic services
- ▶ Cryptographic algorithm that is used (along with their strength)

The use of ICSF cryptographic usage tracking is an efficient way to build, over time, an inventory of the cryptographic algorithm usage and identify the candidate to a migration to quantum-safe algorithm.

Because ICSF cryptographic usage tracking data is stored in SMF records, you can use the ICSF samples to format the records. You can also use other tools, such as IBM Security zSecure Audit, for reporting purposes.

You also can send your cryptographic usage to security information and event management (SIEM) software, such as IBM Security zSecure Adapter for SIEM, which can act as a central repository for tracking cryptographic algorithm usage real time.

A use case for the use of ICSF cryptographic usage tracking is a first view of your production application environments to identify where ICSF cryptographic services (and what algorithm) are being used. From the SMF records, you can identify all the cryptographic services that are used by applications, middleware, or infrastructure components.

After the classification of the results (which are identified as non-quantum-safe algorithm and which are quantum-safe), you can prioritize your approach and use other tools to further complete the inventory.

Later, the results of this analysis, which are classified as quantum-safe, can be analyzed with other tools to complete your cryptographic inventory.

IBM Application Discovery and Delivery Intelligence

IBM Application Discovery and Delivery Intelligence (ADDI) is an analytical platform for application modernization. It uses cognitive technologies to analyze mainframe applications and quickly discover and understand interdependencies of changes.

By using ADDI and the Crypto Analysis function, you can:

- ▶ Discover where and what cryptography is used in applications
- ▶ Support migration and modernization planning:
 - Quickly reacting to security issues
 - Store results in a repository
- ▶ Capture valuable metadata and dependencies:
 - Identifies ICSF Crypto APIs
 - Identifies Rule Array and other important parameters

For example, you know that one of your critical applications (written in COBOL) is using cryptography, but you do not know exactly how this encryption capability was implemented and what encryption algorithm (and “options”) were used.

By using ADDI and its Crypto Analysis, you can quickly import the COBOL source and discover what ICSF cryptographic APIs and parameters were used.

For more information, see “Using IBM Application Discovery and Delivery Intelligence” on page 77.

IBM Crypto Analytics Tool

The IBM Crypto Analytics Tool (CAT) was developed to help provide up-to-date monitoring of cryptography-related information about z/OS in the enterprise. CAT is designed to combine and present cryptographic information in a way that helps ensure compliance and policy enforcement.

The CAT Agent, running on z/OS, collects cryptographic information across the enterprise that is then made available through an IBM Db2® for z/OS database to the CAT Monitor that is running on your desktop.

The CAT Monitor provides overviews, queries, and reports to better manage the cryptographic setup.

With CAT, you can generate reports on your cryptographic configuration, compare the reports, and define and apply policy to your cryptographic elements (cryptographic cards, keys, and so on).

CAT also helps you identify any cryptographic object that is not quantum-safe in your current keystores. CAT also provides monitoring over time to ensure that no non-quantum-safe cryptographic object are created.

For example, if your applications use encryption through middleware, you can identify the keys in the keystore that belong to this application with the CAT Monitor. You also can verify how cryptographic security was implemented to protect cryptographic objects, and who can access them⁸.

For more information, see “Using IBM Crypto Analytics Tool” on page 82.

IBM z/OS Encryption Readiness Technology

z/OS Encryption Readiness Technology (zERT) is a Communications Server feature that provides information about the cryptographic network protection state of TCP/IP and Enterprise Extender connections that end on a z/OS system.

zERT writes its data collection in SMF records (SMF type 119 subtype 11 and subtype 12).

zERT helps you answer the following questions:

- ▶ What TCP/IP and Enterprise Extender traffic is being protected (and which is not)?
- ▶ How is that traffic protected? For example, what protocols are being used, which cryptographic algorithms are being used, and what key lengths?
- ▶ Who on my z/OS system uses or produces the network traffic, whether it is protected or not?
- ▶ Where is the remote endpoint for that traffic?
- ▶ With zERT policy-based enforcement, you can write rules to enforce real-time compliance monitoring that can generate audit events and even take defensive actions that are based on the observed cryptographic protection attributes of each TCP/IP connection.

⁸ Only when using IBM RACF

A z/OS Management Facility (z/OSMF) plug-in that is called IBM zERT Network Analyzer is provided since z/OSMF V2R4⁹. IBM zERT Network Analyzer is a web-based graphical user interface¹⁰ that z/OS network security administrators can use to analyze and report on data that is reported in zERT Summary records (SMF type 119 subtype 12).

By using IBM zERT Network Analyzer, you can build your own cryptographic inventory for data that is in-flight by using its reporting capabilities. The reports can be exported in CSV format to be integrated in enterprise-level repository, if needed.

Finally, starting with z/OS 2.5, zERT provides a feature that is called zERT Policy Enforcement. With zERT Policy Enforcement, you can define required network security policy, including the encryption algorithm in use and then, direct the TCP/IP stack to take specific actions for connections that do not meet that defined policy.

When triggered, the policy can take the following actions to keep your environment quantum-safe:

- ▶ Allow the connection with no logging
- ▶ Write an audit record by using the System Management Facility (SMF) or real-time Network Management Interface (NMI)
- ▶ Write a syslog daemon message
- ▶ Write a console message
- ▶ Reset the connection

For more information, see “Using IBM z/OS Encryption Readiness Technology” on page 89.

4.2.3 Considering cryptographic agility

Cryptographic agility is about the ability to quickly adopt new cryptography in an application, component, or system with minimal impact to the underlying infrastructure. Over time, we saw and understand that cryptographic algorithms change.

However, many applications used hardcoded cryptographic primitives that might not be easy to change. Going forward, we must consider ways to make it as easy as possible to manage the cryptography that is in use in our enterprises.

Several dimensions of agility must be considered (see Table 2-4 on page 25):

- ▶ Update cryptographic algorithms when broken
- ▶ Change cryptographic algorithms when new regulatory requirements exist
- ▶ Monitor cryptographic algorithms to ensure that those algorithms are used correctly
- ▶ Retire cryptographic algorithms when obsolete

Cryptographic agility is a core component of cyber resiliency. If a cryptographic algorithm is found to no longer be secure, the ability to switch to a secure algorithm quickly is essential. We must consider effective ways to manage and use cryptography and automation to simplify the transition to new cryptography.

One way to achieve cryptographic agility is to decouple the cryptographic algorithm from the application code, which makes the change to another encryption algorithm faster, without changing the application code again.

⁹ Also supported by z/OS 2.3 and PTFs for zERT Network Analyzer V2R3 APAR PH03137 and z/OSMF V2R3 APARs PH04391 and PH00712.

¹⁰ IBM Db2 11 for z/OS or later is required.

For example, Advanced Crypto Service Provider (ACSP) can be used to provide an abstraction layer between the application code and the encryption of data by using the IBM Z capabilities.

Advanced Crypto Service Provider

The enterprise cryptographic environment can be spread over several different systems with individual HSMs and application landscape. Therefore, ensuring that all the platforms and environments are remaining quantum-safe might be a challenge.

To help achieve cryptographic agility in a client/server environment, you can centralize the execution of cryptographic operations and establish Crypto-as-a-Service.

One of the IBM Z solutions for establishing Crypto-as-a-Service is to use the cryptographic provider Advanced Crypto Service Provider (ACSP).

With ACSP, you can use your low-used IBM Z cryptography and make it available for all your platforms where applications must use quantum-safe cryptography.

By using the User Defined Functions (UDF) with ACSP, you can implement business-specific functions that are made available through ACSP where the application requests cryptography, without needing to handle the encryption by alone. This ability makes the application crypto-agile because the cryptographic policy is applied at the ACSP server level, which ensures that the correct algorithm is used to encrypt and decrypt the data (see Figure 4-6).

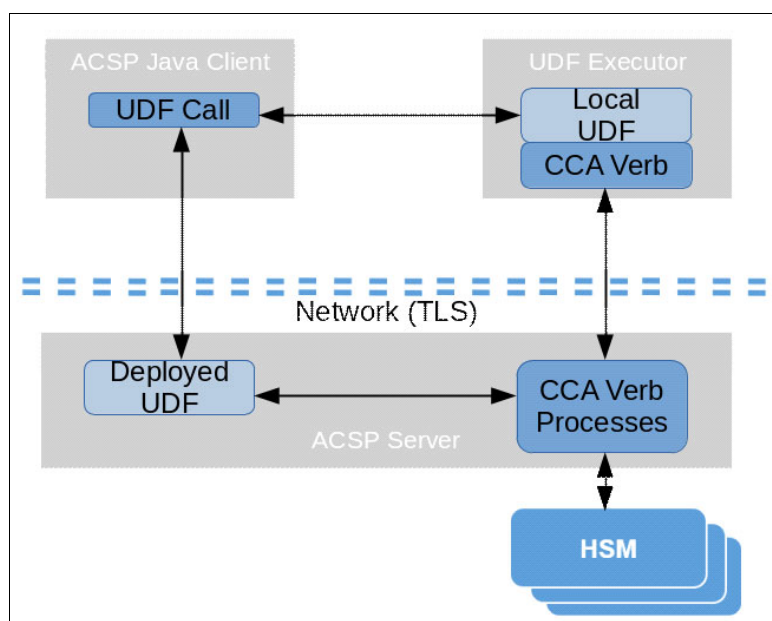


Figure 4-6 UDF calling path for a local and deployed set-up

A possible architecture that implements cryptographic agility by using ACSP is shown in Figure 4-7.

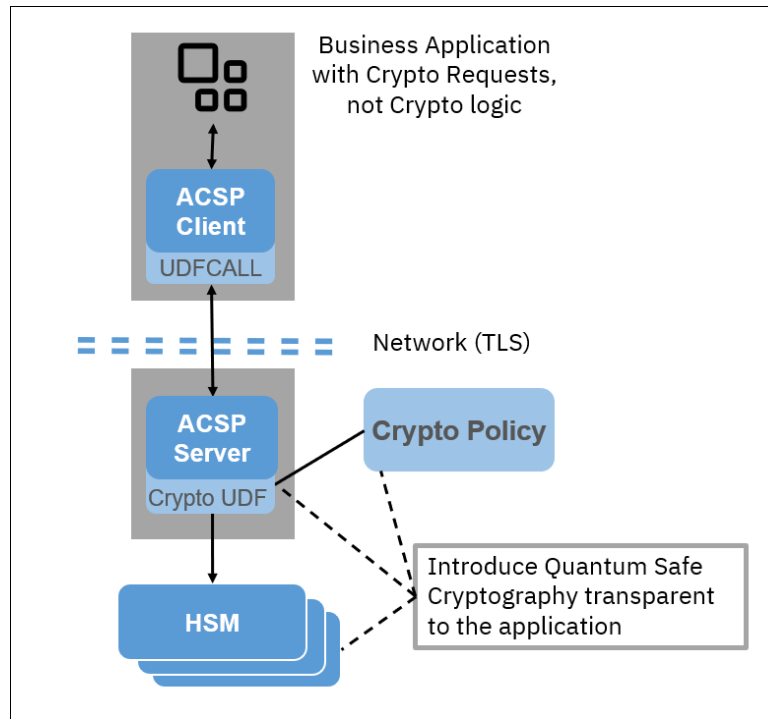


Figure 4-7 ACSP architecture used for cryptographic agility

4.2.4 Adopting quantum-safe cryptography

After you know your current cryptography state, examine the technical mitigations that are available to you. Understand who can provide the necessary technology. Determine which options must be applied to each of your use cases.

For more information about common use case examples, see Chapter 3, “Using quantum-safe cryptography” on page 27.

A risk assessment is performed to determine the priority of implementation and testing. Some implementation options include strengthening the symmetric algorithms that are used for data protection.

Use hybrid key exchange methods or dual signing schemes that use classical and quantum-safe algorithms. When necessary, the use of physical isolation techniques also is an option because it keeps critical information off the network and puts data on systems that feature restricted access and controls in place.

Educating your teams about the options and early planning and testing is key to having a successful quantum-safe transition experience.

When all of the data, application, and cryptographic key and algorithm information is collected and recorded and a priority list established, the implementation phase can start. A sample cryptographic inventory sheet is shown in Figure 4-8.

Data Type/Asset	Owner	Crypto usage/algorithm	Other platforms/applications	Mitigation/ Quantum-safe required	Priority
Data_1	Owner_1	Data encryption, AES 256	n/a	n/a	n/a
Data_2	Owner_2	Data encryption, DES	x86	AES 256	2
Data_3	Owner_1	Digital Signature SHA256, RSA	n/a	Replace by CRYSTALS-Dilithium	1

Figure 4-8 Sample cryptographic inventory sheet

Based on the discovered items, the applications (or infrastructure components) must move to quantum-safe encryption if they are not quantum-safe (AES 256 is quantum-safe).

An example of a non-quantum-safe condition is an application that signs data with RSA. To make it quantum-safe, a dual signature scheme is used following NIST recommendations.

A dual signature consists of two (or more) signatures on a common message. The verification of the dual signature requires all of the component signatures to be successfully verified.

In a dual signature, one signature is generated with a NIST-approved signature scheme as specified in FIPS 186, while another signatures can be generated by using a different algorithm.

Dual signatures can be accommodated by current standards in “FIPS mode,” as defined in FIPS 140, if at least one of the component methods is a correctly implemented, NIST-approved signature algorithm. It is up to the application to specify how to parse signatures and verify them separately.

For more information, see the following resources:

- ▶ This [NIST post-quantum cryptography \(PQC\) web page](#)
- ▶ This [French National Cybersecurity Agency \(ANSSI\) web page](#)

Some technical environment upgrades or modifications might be required to support quantum-safe cryptography. For more information, see 4.1, “IBM Z cryptographic components overview” on page 48, and “Ensuring the environment is ready” on page 101.

4.2.5 Where to find help at IBM

IBM Systems Lab Services offers a quantum-safe assessment, which is a useful way to quickly understand how your company uses IBM Z cryptographic features and to inventory the cryptography in use today to maximize quantum-safe capabilities of your IBM Z environment.

The assessment analyzes current best practices and provides a practical roadmap of actions to strengthen your quantum-safe posture.

For more information, email us at <mailto:ibmsls@ibm.com>.

4.3 Best practices, mitigation options, and tools

This section provides information about how to use security best practices to build a secure z/OS cryptographic environment. It also includes some mitigation options that you can use along with an introduction to the key management tools, which must be considered during your quantum-safe journey.

4.3.1 ICSF best practices

Implementing a secured cryptographic environment on z/OS is the foundation for building a strong quantum-safe cryptographic environment. The following sections describe best practices for ICSF.

ICSF configuration

ICSF more likely is the repository for all of your keys. Therefore, you must ensure it is configured for the maximum level of security for your encrypted data. We suggest configuring ICSF by using the following settings:

- No compatibility/coexistence mode

Compatibility mode was introduced to run applications written with Programmed Cryptographic Facility (PCF), ICSF ancestor, without reassembling the application. Because these applications likely use weak non-quantum-safe algorithm, they must be converted to ICSF and use quantum-safe algorithm.

If you still use AMS REPRO encryption (which requires compatibility mode), you must use other means to encrypt your data. IDCAMS ENCRYPT/DECRYPT works with weak 56-bit DES key (no Triple DES support).

Also, changing the master keys in compatibility mode requires an IPL of the system.

Verify that the parameter COMPAT(YES) or COMPAT(COEXIST) is not specified in CSFPRMxx. The default is COMPAT(NO).

- No special secure mode

When special secure mode (SSM) is enabled, ICSF enables the generation or entry of clear keys, which lowers the security of the system. Clear keys usage should not be allowed.

Verify that the parameter SSM(YES) is not specified in CSFPRMxx. The default is SSM(NO). SSM can also be enable by a CSF.SSM.ENABLE.SAF profile in the XFACILIT resource class. Ensure it is not defined.

- Allocation of the xKDS

The xKDS data sets that are managed by ICSF more likely contain all of your keys. You must ensure that the initial allocation of these data sets allows growth.

To support quantum-safe keys, the xKDS must be in KDSRL format (see SYS1.SAMPLIB(CSFCDS) and SYS1.SAMPLIB(CSFPKDS) as provided with ICSF HCR77D2 (z/OS 2.5).

The CKDS, PKDS contains one initialization record with the values of the current master keys verification patterns (MKVPs) for the type of keys that are stored in the keystore (AES and DES MKVPs for the CKDS, ECC, and RSA MKVPs for the PKDS).

Then, each VSAM record contains one key.

The default found in the SYS1.SAMPLIB allocates a CKDS with 200 keys in the primary extent and 100 in each secondary extent. It also allocates a PKDS with 100 keys in the primary extent and 50 in each secondary extent.

When allocating your CKDS, consider your number of keys and the growth that is expected from a data encryption perspective. This growth must include key rotation in the coming years and factor how long you must keep old keys “alive” in your CKDS to access old data from backups you must keep for regulatory purposes.

An installation that includes 100 keys in their CKDS, an application encryption requirement growth of 10% per year, rotates their operational keys every year, and a 10-year data retention period must be prepared to store more than 500 keys.

Taking a large margin and over-allocating the CKDS to 1000 records in the primary extent uses only 10 tracks total (VSAM DATA + INDEX).

ICSF and z/OS security best practices

These z/OS security best practices aid in enhancing the protections across the z/OS cryptographic stack. Locking down the z/OS cryptographic stack enables you to realize the following benefits:

- ▶ Reduce the attack surface of your z/OS environment
- ▶ Enable routine security hygiene practices
- ▶ Use new capabilities and features
- ▶ Meet regulatory compliance requirement

Key label naming conventions

Cryptographic keys that are stored in the ICSF key data sets can be referenced by their key label. A key label can be up to 64 characters and consist of alphanumeric characters, national characters (#, \$, @), or a period. When determining a key label name, consider the following factors:

- ▶ LPAR that is associated with the key
- ▶ Type of data that is encrypted
- ▶ Owner that is associated with the key
- ▶ Date that the key was created
- ▶ Application that uses the key
- ▶ A sequence number for the key

Consider the following key label example:

SYS1.DB2.ENCKEY.202204.0001

Protecting cryptographic keys and ICSF services

Access to CCA cryptographic keys is controlled through the CSFKEYS general resource class. When a key is used in an application, ICSF checks for a discrete CSFKEYS profile that matches the key's label.

If a covering profile (discrete or generic) exists, access to the key is granted based on whether the user or group has READ access. By default, the CSFKEYS class grants access to the key if no profile is in place.

Ensure that the CSFKEYS class is ACTIVE and RACLISTed and a backstop profile exists; for example, '*' or '**' with UACC(NONE).

Access to PKCS #11 tokens is controlled through the CRYPTOZ general resource class. By default, the CRYPTOZ class does not grant access to the PKCS #11 token if no covering profile exists.

Ensure that the CRYPTOZ class is ACTIVE and RACLISTed. Define USER.* and SO.* backstop profiles with UACC(NONE).

For more information about protecting PKCS #11 tokens with the CRYPTOZ class and the USER and SO (Security Officer) rules, see *z/OS ICSF Writing PKCS #11 Applications*, SC14-7510.

Access to ICSF callable services is controlled through the CSFSERV general resource class. When an ICSF service is called, ICSF checks for a discrete CSFSERV profile that matches the service name. By default, access to most ICSF services is granted if no covering profile exists.

Also, ensure that the CSFSERV class is ACTIVE and RACLISTed. Define a backstop profile; for example, '*' or '**' with UACC(NONE).

Key lifecycle and key usage auditing

ICSF instances can be configured to audit the lifecycle of keys as they transition through the system. Keys can be audited from the time of their initial generation until their eventual deletion. Key lifecycle audit data is written as SMF Type 82 subtype 40, 41, and 42 records.

ICSF key lifecycle auditing includes the following options:

- ▶ AUDITKEYLIFECKDS: In the CKDS
- ▶ AUDITKEYLIFECPKDS: In the PKDS
- ▶ AUDITKEYLIFETKDS: In the TKDS

Key Lifecycle auditing can be enabled in the ICSF installation options data set or dynamically by using the **SETICSF** command.

ICSF instances can be configured to audit key usage. Key usage data can be used to determine which key was used, who used the key, and when the key was used. Key usage audit data is written as SMF Type 82 subtype 44, 45, 46, and 47 records.

ICSF key usage auditing includes the following options:

- ▶ AUDITKEYUSGCKDS: CCA symmetric tokens
- ▶ AUDITKEYUSGPKDS: CCA asymmetric tokens
- ▶ AUDITPKCS11USG: EP11 keys

Key usage auditing can be enabled in the ICSF installation options data set or dynamically by using the **SETICSF** command.

For more information about ICSF key lifecycle and key usage auditing, see *z/OS ICSF System Programmer's Guide*, SC14-7507.

SAF protecting the ICSF Key Data Sets

ICSF Key Data Sets contain the CCA and EP11 cryptographic keys that are used within ICSF callable services. Although use of the keys can be protected with the CSFKEYS and CRYPTOZ general resource classes, the Key Data Sets also must be SAF protected.

Without sufficient SAF protections on all three ICSF Key Data Sets, the ICSF keys are at a greater risk of becoming compromised. Regardless of whether you use clear or secure keys, each of your ICSF Key Data Sets must include a DATASET profile with UACC(NONE).

Backing up ICSF keys

It is important to adopt a routine schedule of backing up the ICSF keystores. Backing up the keystore is recoverable. By regularly backing up the DASD volumes that contain the key stores, the entire volume can be restored if the volume becomes corrupted.

Also, create backups before and after major key management operations. For example, performing an unfamiliar key management operation, generating many new keys, or after a master key rotation.

When creating your backup, consider whether you should have an online or offline backup. An online backup provides the quickest recovery from a corrupted keystore or deletion, but it is also susceptible to attack by a bad actor.

An offline backup (for example to tape) safeguards a keystore from being compromised by malicious software with access to online devices. Although offline backups might not be as up to date, they are less likely to be compromised.

If you are using or plan to implement z/OS data set encryption, we suggest that you deploy a robust key management solution, especially as the number of keys to manage increases.

For more information about calculating the number of encryption keys you might need for your environment, see this [IBM Support publication](#).

4.3.2 Mitigation options

z/OS includes many features and functions that directly provide quantum-safe encryption for your data when at-rest or when a quantum-safe digital signature is used. The use of quantum-safe encryption algorithm for data-at-rest can provide the following mitigation options if the data remains encrypted while in transit:

- z/OS data set encryption

When implemented, z/OS data set encryption provides a high level of protection for your sensitive data when stored in z/OS data sets (extended format sequential data sets, extended format VSAM data sets, and basic and large nonextended format sequential data sets).

z/OS data set encryption is based on AES-XTS block cipher mode with keys of 256 bits strength; therefore, it is considered quantum-safe.

Also, z/OS data set encryption does not require application changes when it is implemented; therefore, it ensures a short path to quantum-safe encryption.

- JES2 spool encryption

Because JES2 spool encryption is based on the same technology as z/OS data set encryption, the same level of protection to your data is provided during and after job execution.

This option is another a short path to quantum-safe encryption.

- Digital signature and SMF

It is important to protect your data and the data of your clients or Business Partners, but it is also important to ensure that audit trails are not tampered. SMF digital signature provides an easy way to digitally sign the SMF records.

When written to the log stream, the SMF records are hashed and SMF periodically signs the hash by using a private key.

When reading the records, the utility program IFASMFDP verifies that the records were not corrupted or tampered.

The alternative signature algorithm introduced the use of Dilithium digital signature with RSA or ECDSA, which makes SMF digital signing quantum-safe. This support requires an IBM z15 or IBM z16 environment for the entire sysplex.

4.3.3 Key management tools

The use of a quantum-safe cryptographic algorithm is only a first step. Correctly managing the keys that are used by these cryptographic algorithms also is important to ensure they are safely stored and transported and maintain compliance.

Trusted Key Entry

TKE is an integrated solution that manages cryptographic keys, such as master keys and initial key encrypting keys (KEKs) in a secure environment. The TKE Workstation enables basic local and remote key management. It is an optional hardware feature of IBM Z that provides a management tool for IBM Z host cryptographic coprocessors.

The TKE feature contains a combination of hardware, firmware, and software. For more information, see this [IBM Z and LinuxONE Content Solutions web page](#).

In a quantum-safe environment, it is paramount that all master keys in the xKDS are safely managed and stored. Master keys should *never* be exposed in the clear or wrapped with non-quantum-safe keys in a virtual safe.

With TKE, all the keys are generated in a cryptographic adapter coprocessor in the workstation and are never accessible in the clear. Even if optional, we recommend the use of TKE with smart card readers and smart cards to store and backup the keys. This configuration ensures the highest level of security and compliance.

With IBM z16 and TKE v10.0, a CRYSTALS-Kyber handshake occurs between the TKE Workstation cryptographic adapter and the target Crypto Express HSM when CCA master key parts are loaded into the target.

Note: Crypto Express8S and Crypto Express7S features that include quantum-safe capabilities that are enabled cannot be in the same TKE domain group as those features without quantum-safe capabilities enabled.

IBM Enterprise Key Management Foundation

Enterprise Key Management Foundation (EKMF) is a flexible and highly secure key management system for the enterprise. It provides centralized key management on IBM Z and distributed platforms for streamlined, efficient, and secure key and certificate management operations.

EKMF consists of an independent workstation (with IBM 4767 cryptographic coprocessors), and software that ensures a high security environment. For more information, see the [IBM EKMF web page](#).

All keys and certificates are stored in a central repository with metadata, such as activation dates and usage. By storing all key material in a central repository, backup is easily achieved by including the database in database backup procedures. This feature facilitates easy recovery if keys or certificates are lost.

You can transition to the EKMF Workstation at any time during your quantum-safe encryption journey. The EKMF Key Remote Store Viewer and Importer is available for that purpose.

The EKMF Workstation supports CRYSTALS-Dilithium (see Figure 4-9).

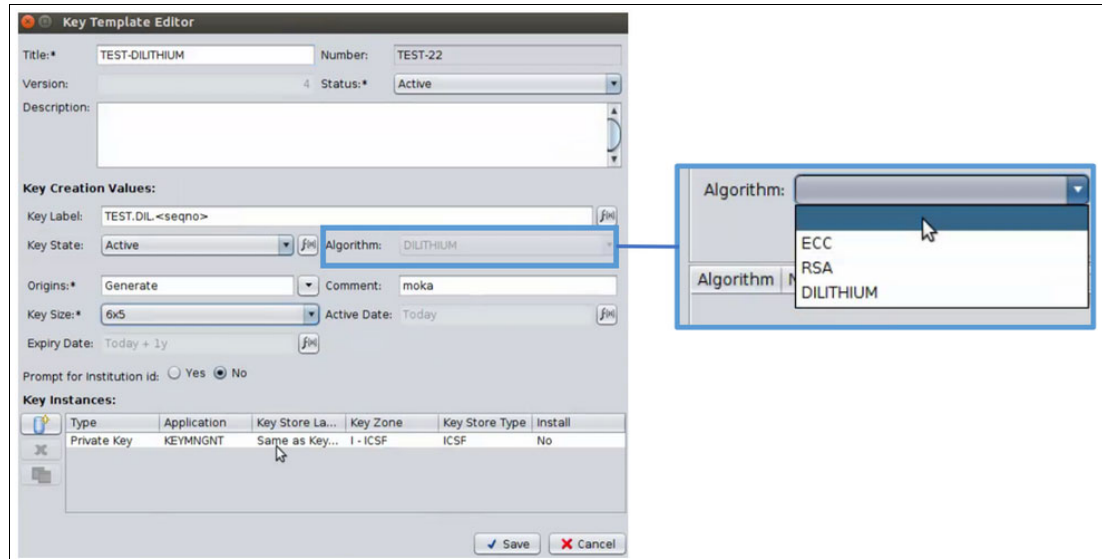


Figure 4-9 EKMF Workstation CRYSTALS-Dilithium support



Creating a cryptographic inventory

Before transitioning to quantum-safe algorithms, it is important to create a cryptographic inventory that covers all aspects of cryptography in your enterprise. This process includes classifying the data to help you identify where your sensitive data is stored inside and outside the IBM Z environment.

The cryptographic inventory also lists the certificates, encryption protocols, algorithms, and key lengths that are used and indicates those that are weakened by quantum computers. For more information about for an approach for creating a cryptographic inventory, see “Establishing a cryptographic inventory” on page 58.

This chapter shows you how to configure, run, and interpret the results for each of the cryptographic inventory creation tools and includes the following topics:

- ▶ 5.1, “Collection tools overview” on page 72
- ▶ 5.2, “Using ICSF cryptographic usage tracking” on page 73
- ▶ 5.3, “Using IBM Application Discovery and Delivery Intelligence” on page 77
- ▶ 5.4, “Using IBM Crypto Analytics Tool” on page 82
- ▶ 5.5, “Using IBM z/OS Encryption Readiness Technology” on page 89

5.1 Collection tools overview

IBM provides several tools that can aid in the cryptographic discovery process and developing a cryptographic inventory for your IBM Z environment. Each tool provides unique information for creating a cryptographic inventory:

- ▶ IBM z/OS Integrated Cryptographic Service Facility (ICSF) cryptographic usage tracking records are written as SMF records aggregating usage of cryptographic engines, cryptographic services, and cryptographic algorithms.
- ▶ IBM Application Discovery and Delivery Intelligence (ADDI) analyzes COBOL application files that capture valuable metadata and dependencies by identifying important ICSF parameters for crypto algorithms.
- ▶ IBM Crypto Analytics Tool (CAT) creates snapshots of the z/OS environment by extracting security and cryptographic information that is based on defined policies.
- ▶ IBM z/OS Encryption Readiness Technology (zERT) collects and reports the cryptographic security attributes of IPv4 and IPv6 application traffic that is protected by using the TLS/SSL, SSH, and IPsec cryptographic network security protocols.

After the information is collected, perform a gap analysis to determine whether business, compliance, and audit requirements are being met. The gap analysis aids you in prioritizing updates for your environment.

For more information about a process for making use of the various tools to identify the cryptographic algorithm, key length, and key label information that is related to COBOL programs, see Appendix A, “Finding cryptographic attributes” on page 121.

5.2 Using ICSF cryptographic usage tracking

Beginning with ICSF FMID HCR77C1, ICSF instances can be configured to collect cryptographic usage data when crypto operations are performed by that ICSF instance. ICSF creates an SMF record type 82, subtype 31 to aggregate crypto usage statistics for each job or user that is associated with the crypto usage in a specified period.

Note: It is essential to collect the records over a sufficient period, capturing as much workload and key usage as possible. This process helps build a more comprehensive cryptographic inventory.

ICSF cryptographic usage tracking (see Figure 5-1) features the following options for collecting statistics:

- ▶ ENG: Crypto Express adapters, CPACF, and software
- ▶ SRV: ICSF callable services and UDXes
- ▶ ALG: Cryptographic algorithms that are used within ICSF crypto operations

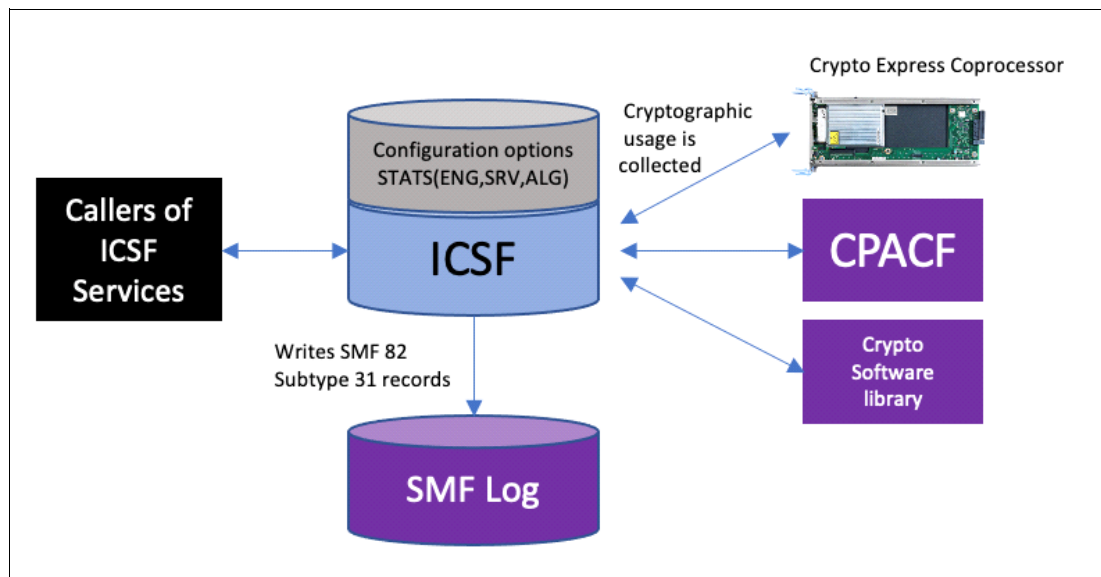


Figure 5-1 ICSF cryptographic usage tracking overview

5.2.1 Configuring SMF for ICSF cryptographic usage tracking

Before ICSF can write SMF records for cryptographic usage, the SMFPRMxx member in PARMLIB (see Example 5-1 on page 74) must be updated to contain the following components:

- ▶ The collection interval (INTVAL).

Cryptographic usage tracking is synchronized to the SMF recording interval. In our example, ICSF records crypto usage every 5 minutes.

- ▶ The synchronization value (SYNCVAL).

Synchronizes the recording interval with the end of the hour of the TOD clock. In our example, ICSF starts recording crypto usage at the end of the hour.

- The Cryptographic Usage Statistics subtype 31 for ICSF type 82 records (TYPE).
Specifies the type of records to be recorded. In our example, SMF 82 subtype 31 is specified.

Example 5-1 SMFPRMxx member example

```

DSNAME(SMF.MANA,SMF.MANB)          /* SMF Data sets          */
INTVAL(05)                          /* INTERVAL - 5 minutes */
SYNCVAL(00)                        /* SYNCHRONIZATION - 0 minutes */
SYS(TYPE(0,2,3,82(31),83,128:132)) /* ICSF SMF 82 subtype 31 */

```

5.2.2 Enabling cryptographic usage tracking within ICSF

Cryptographic usage tracking can be enabled within ICSF by using one of the following methods:

- Through the installation options that are used for ICSF initialization
The CSFPRMxx member in PARMLIB must contain the STATS option. As shown in Example 5-2, all three STATS options are enabled. STATS(ALG) must be specified to enable algorithm usage tracking. STATSFILTERS(NOTKUSERID) can be optionally specified to exclude the task level user ID from the stats aggregation criteria. This option is intended for environments that features a high volume of operations that are running under task level user IDs, which reduces the number of SMF 82 Subtype 31 records written.

Example 5-2 CSFPRMxx options

```

CKDSN(SYS1.CKDS)
PKDSN(SYS1.PKDS)
TKDSN(SYS1.TKDS)
STATS(ENG,SRV,ALG)
STATSFILTERS(NOTKUSERID)

```

- Dynamically enable cryptographic usage tracking by using the **SETICSF** command (see Example 5-3).

Example 5-3 SETICSF command

```

SETICSF OPT,STATS=(ALG)

```

The STATS setting can be verified by using the **DISPLAY ICSF,OPT** command (see Example 5-4).

Example 5-4 DISPLAY ICSF,OPT output

```

D ICSF,OPT
CSFM668I 12.44.17 ICSF OPTIONS 907
  SYSNAME = SY1          ICSF LEVEL = HCR77D2
  LATEST ICSF CODE CHANGE = 02/21/22
  Refdate update interval in Days/HH.MM.SS = 005/00.00.00
  Refdate update period   in Days/HH.MM.SS = 000/01.00.00
  MASTERKCVLEN = display ALL digits
  AUDITKEYLIFECKDS: Audit CCA symmetric key lifecycle events
    SYSNAME  LABEL  TOKEN
    SY1      Yes    Yes
  AUDITKEYLIFECPKDS: Audit CCA asymmetric key lifecycle events
    SYSNAME  LABEL  TOKEN

```



```

SY1          Yes      Yes
AUDITKEYLIFETKDS: Audit PKCS #11 key lifecycle events
SYNAME      TOKOBJ    SESSOBJ
SY1          Yes      Yes
AUDITKEYUSGCKDS: Audit CCA symmetric key usage events
SYNAME      LABEL     TOKEN      Interval Days/HH.MM.SS
SY1          No       No          000/02.00.00
AUDITKEYUSGPKDS: Audit CCA asymmetric key usage events
SYNAME      LABEL     TOKEN      Interval Days/HH.MM.SS
SY1          No       Yes          000/01.00.00
AUDITPKCS11USG: Audit PKCS #11 usage events
SYNAME      TOKOBJ    SESSOBJ    NOKEY  Interval Days/HH.MM.SS
SY1          No       No          Yes    000/05.00.00
STATS:
SY1          ALG
COMPLIANCEWARN: Compliance warning events
SY1          PCI-HSM 2016      Yes
TRACKCLASSUSAGE:
SY1          NONE

```

5.2.3 Formatting cryptographic usage statistics records

After ICSF cryptographic usage tracking is enabled for algorithms, run applications on the ICSF instances with tracking enabled. As a result, SMF cryptographic usage records are generated.

ICSF provides formatters in SYS1.SAMPLIB (CSFSMFJ) that is the JCL that can be submitted to read SMF record type 82 and format them into a report. CSFSMFR is the REXX exec that is used to run the report against the SMF records.

A formatted report of SMF record type 82, subtype 31 (hex '001F') is shown in Example 5-5.

Example 5-5 Formatted report of SMF record type

```

Type=82 Subtype=001F Crypto Usage Statistics
Written periodically to record crypto usage counts
22 Feb 2022 15:12:27.73
TME... 005389D5 DTE... 0122053F SID... SP21      SSI... 00000000 STY... 001F
INTVAL_START.. 02/22/2022 19:11:30.001815
INTVAL_END.... 02/22/2022 19:12:27.737573
USERID_AS.....DATAOWN
USERID_TK.....
JOBID.....J0000055
JOBNAME.....DATAOWN
JOBNAME2.....
PLEXNAME.....SYS1
DOMAIN.....0
ENG...CARD...8C11/99EA6127...17
ENG...CPACF...150
ALG...DES56.....2
ALG...AES128.....2
ALG...RSA1024....1
ALG...ECCBP192...1
ALG...MD5.....45
ALG...RPM160....15

```

```

ALG...SHA1..... 70
ALG...SHA3-224... 13
ALG...SHA3-256... 15
ALG...SHA3-384... 13
ALG...SHA3-512... 13
ALG...SHAKE128... 12
ALG...SHAKE256... 14
SRV...CSFKYT..... 2
SRV...CSFD SG..... 2
SRV...CSFOWH..... 264
SRV...CSFOWH1.... 3
SRV...CSFIQF..... 485
SRV...CSFIQF2.... 2
*****

```

Interpreting cryptographic usage statistics SMF records

After you formatted the cryptographic usage statistics SMF records, you can begin identifying algorithms that are used in applications that must be replaced.

In Example 5-5 on page 75, algorithms DES56, AES128, and RSA1024 were used in crypto operations within the SMF recording interval. The SMF record lists the HOME address space ID or HOME address space job name, which are the job or task that started the cryptographic request.

The SMF record also can list the SECONDARY address space job name (for example, the caller that made the program call or space switch to ICSF), the HOME address space user ID, and the task level user ID if available.

In Example 5-5 on page 75, the usage event is recorded for jobname DATAOWN. It occurred on system SYS1 and used crypto domain 0.

DES56, RSA1024, AES128, SHA-1 are examples of weak algorithm candidates to prioritize for migration in your cryptographic inventory.

5.3 Using IBM Application Discovery and Delivery Intelligence

IBM ADDI (see Figure 5-2) is an analytics platform for mainframe application modernization. It identifies and visualizes application dependencies and helps you quickly understand the impact of changes.

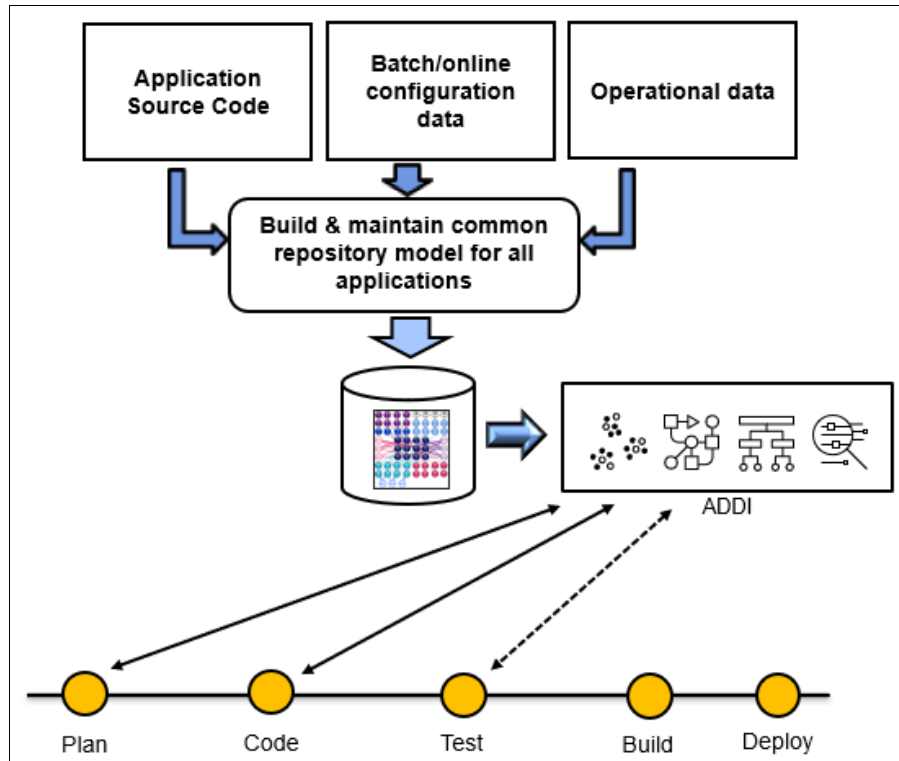


Figure 5-2 IBM ADDI flow

IBM Application Discovery Build Client is part of the IBM ADDI product suite. By using IBM Application Discovery Build Client to perform application crypto analysis, you can realize the following benefits:

- ▶ Efficiently locate and identify where crypto is used in applications.
- ▶ Capture valuable metadata and dependencies by identifying important ICSF parameters, such as “Rule Array”.
- ▶ Store analysis results in a repository.
- ▶ Plan migration and modernization efforts.
- ▶ React quickly to potential security issues.

Note: As of this writing, this support is available for COBOL applications only.

5.3.1 Configuring IBM AD Build Client for ICSF crypto analysis

The following steps assume that the installation and configuration process is complete for ADDI. For more information about this process, see this [IBM Documentation web page](#).

Complete the following steps to configure and run IBM Build Client against your COBOL application:

1. Verify that the CRYPTO resolutions file (CAPIResolutions.json) is available in the \bin\release folder. This folder is where the AD Build Client executable (IBMApplicationDiscoveryBuildClient.exe) is stored.

The following default path is used by the installation:

C:\Program Files\IBM Application Discovery and Delivery Intelligence\IBM Application Discovery Build Client\bin\release

Note: After the installation is complete, CAPIResolutions.json can be found in the \bin\release\Samples folder. Copy the .json file and place it in the bin\release folder.

2. Open the AD Build Client tool and create a project by clicking **File** → **New** → **New Project** (see Figure 5-3).

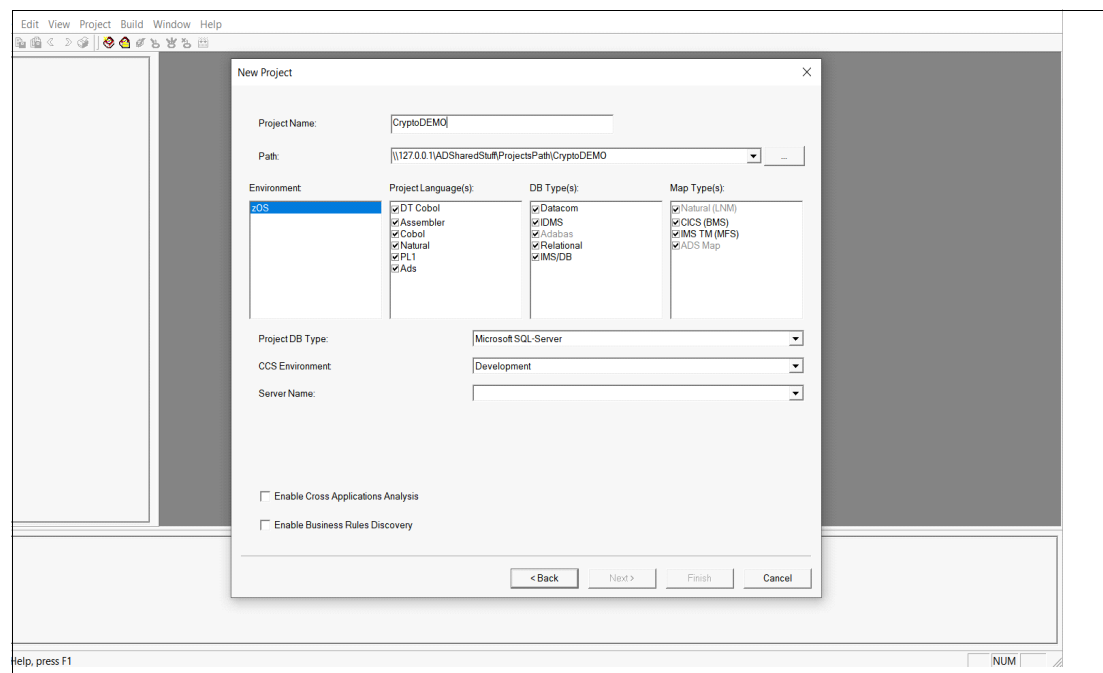


Figure 5-3 Creating an IBM AD Build client

3. Upload your COBOL application files to the project. You should download these files from your mainframe. These COBOL files are scanned and analyzed for CALL statements, which are calls to ICSF cryptographic services. Complete the following steps:
 - a. Right-click **zOS Cobol** project folder → **Add Files**.
 - b. Locate the files on your local machine, select them, and click **OK**.
 - c. Repeat step 2 until all application files are added to the project.

d. After the project tree is populated, click **File** → **Save Project** (see Figure 5-4).

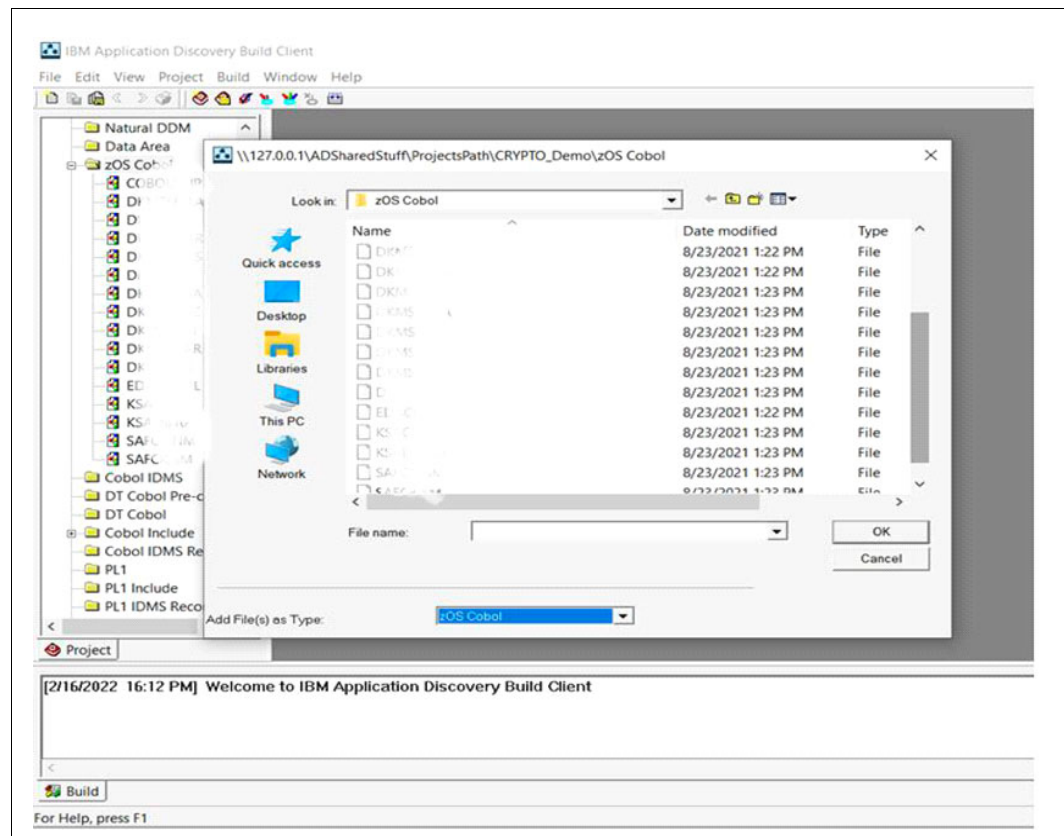


Figure 5-4 IBM AD add COBOL application window

4. Build the project by clicking **Build** → **Build Project**. Then, wait until the build process completes. Two files are generated that are related to ICSF crypto CALLs:
 - GenericAPI_<timestamp>.csv
 - GenericAPI_<timestamp>.html
5. Locate the Project path on disk and the change directory to:


```
<Project path>/Reports/GenericAPI.
```

For example:

```
C:\IBM AD\Mainframe Projects\<your_project_name>\Reports\GenericAPI
```

The .csv file can be read as is or used as input by other tools as raw input.

The .html file can be used as a report where the results can be filtered according to various criteria.

5.3.2 Interpreting IBM AD Build Client file results

In Figure 5-5, each CALL statement is uniquely identified by an ID in column A (OccurID); CALLs to ICSF CRYPTO service are in column B (APIName). The file where the CALL is stored is in column K (PathStr) at the line in column L (StartRow).

The CALLs parameter values are in column G (ParamValue) and form one of more tuples in column H (GroupID), which correspond to the parameter positions column F (OrdinalPos) that is specified in the CAPIResolutions.json for the respective service.

If no CALL statements to ICSF cryptographic services are found within the COBOL source files, an empty report is generated with the message:

GenericAPI query returned no results.

Results Messages													
OccurID	APIName	APIDescription	APIMetadata	OrdinalPos	ParamValue	GroupID	Description	VarName	ProgramName	PathStr	StartRow		
7	60	CSNBDEC	Decipher	DES	10	CUSP	1	CRYPTO	RULE-ARRAY-S	COBOLXMP	126		
8	4717	CSNBEPG	Encrypted PIN Generate	DES	7	1	1	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7356		
9	4717	CSNBEPG	Encrypted PIN Generate	DES	8	IBM-PIN	1	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7356		
10	4747	CSNBKTB	Key Token Build	DES	7	3	1	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7420		
11	4747	CSNBKTB	Key Token Build	DES	8	DES INTERNALDOUBLE WRAP ENH	1	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7420		
12	4767	CSNBKGN	Key Generate	DES	6		1	CRYPTO	CSFSERV-KEY-LENGTH	DKMSKSA	7468		
13	4767	CSNBKGN	Key Generate	DES	7	TOKEN	1	CRYPTO	CSFSERV-KEY-TYP1	DKMSKSA	7468		
14	4767	CSNBKGN	Key Generate	DES	8		1	CRYPTO	CSFSERV-KEY-TYP2	DKMSKSA	7468		
16	4906	CSNBICPA	Clear PIN Generate Alternate	DES	10	2	1	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7705		
18	4906	CSNBICPA	Clear PIN Generate Alternate	DES	11	VISA-PVFPINBLOCK	1	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7705		
17	4906	CSNBICPA	Clear PIN Generate Alternate	DES	10	2	2	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7705		
18	4906	CSNBICPA	Clear PIN Generate Alternate	DES	11	IBM-PINOPINBLOCK	2	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7705		
19	4906	CSNBICPA	Clear PIN Generate Alternate	DES	10	2	3	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7705		
20	4906	CSNBICPA	Clear PIN Generate Alternate	DES	11	IBM-PIN	3	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7705		
21	4906	CSNBICPA	Clear PIN Generate Alternate	DES	10	2	4	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7705		
22	4906	CSNBICPA	Clear PIN Generate Alternate	DES	11	DES INTERNALDOUBLE WRAP ENH	4	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7705		
23	4906	CSNBICPA	Clear PIN Generate Alternate	DES	10	2	5	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7705		
24	4906	CSNBICPA	Clear PIN Generate Alternate	DES	11	REFORMATPINBLOCK	5	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7705		
25	4906	CSNBICPA	Clear PIN Generate Alternate	DES	10	2	6	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7705		
26	4906	CSNBICPA	Clear PIN Generate Alternate	DES	11	CBC CONTINUEDES	6	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7705		
27	4906	CSNBICPA	Clear PIN Generate Alternate	DES	10	2	7	CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	7705		
30	4906	CSNBICPA	Clear PIN Generate Alternate	DES	11	EMPSVOT	7	CRYPTO	CSFSERV-RULE-A	DKMSKSA	7705		

Figure 5-5 IBM AD Build client results example

When reviewing the results, pay attention to the APIMetadata and ParamValue columns. These columns provide insight into the type of algorithms that are used within the ICSF crypto service call. When building your cryptographic inventory, consider adding programs that contain ICSF calls with weak algorithms, such as DES.

5.3.3 Interpreting the CRYPTO CAPIResolutions.json resolutions file

The CRYPTO Resolutions (CAPIResolutions.json) file is a configuration file with the possible API calls, the parameters to capture, and information about ICSF calls. The ADDI build process uses this file to capture the data and can be extended or customized (see Example 5-6).

Example 5-6 CRYPTO Resolution file snippet example

```
{ "formatVersion": "1.0",  
...  
"GenericAPIs":  
[  
...  
  { "GenericAPIName": "CSNBENC1,CSNEENC1",  
    "Description": "Encipher",  
    "Metadata": "DES",  
    "Metadata1": "Encryption/Decryption",  
    "Parameters":  
    [  
      { "Name": "RULE_ARRAY_COUNT",
```

```

        "Position":9,
        "DefaultValues":"0" },
    { "Name":"RULE_ARRAY",
      "Position":10,
      "DefaultValues":"INITIAL, TOKEN" }
  ]
}
...
]
}

```

Where:

- ▶ **GenericAPIName:** Name of the ICSF service (if that service has several names, you can initialize it with all of the values separated by comma)
- ▶ **Description:** Short description of the service
- ▶ **Metadata:** Algorithm used by that service
- ▶ **Metadata1:** Category to which that service belongs
- ▶ **Parameters:** Array of parameter objects where each object includes the following information:
 - **_Name:** Parameter name (for example, for the Rule Array Params column: RULE_ARRAY_COUNT and RULE_ARRAY names are used. For any Other Params, PARAM<No> is used; for example, PARAM6, PARAM7, and PARAM8).
 - **_Position:** Position of that parameter for which we want to collect its values.
 - **_DefaultValues:** Comma-separated default parameter values, if applicable.

5.3.4 Extending the CRYPTO CAPIResolutions.json resolutions file

If you use an abstraction layer within the COBOL source files that is built on top of the standard cryptographic libraries (CCA and ICSF), the CAPIResolutions.json file must be edited and extended with the client interfaces (see Example 5-7).

Example 5-7 Custom CAPIResolutions.json file

```

{
  "GenericAPIName":"MYENCPHR",
  "Description":"Custom Encipher",
  "Metadata":"DES",
  "Metadata1": "Custom Implementation of Encryption/Decryption",
  "Parameters":
  [
    { "Name":"RULE_ARRAY_COUNT",
      "Position":9,
      "DefaultValues":"0"
    },
    { "Name":"RULE_ARRAY",
      "Position":10,
      "DefaultValues":"INITIAL, TOKEN"
    }
  ]
}

```

5.4 Using IBM Crypto Analytics Tool

The IBM CAT provides a graphical interface that is used to search, display, and analyze data that is extracted from the different cryptographic components. The findings are presented in generated reports.

IBM CAT also can apply a set of policy rules that can be used to analyze the extracted data and flag whether the objects are compliant or noncompliant according to the policy rules (such as reporting non-quantum-safe keys).

5.4.1 IBM CAT overview

IBM CAT features the following components (see Figure 5-6):

- ▶ A data collection for z/OS that consists of load modules and compiled REXX execs to extract cryptographic and security-related information from z/OS systems. The extracted data is loaded into the IBM Crypto Analytics Tool DB2® database and provides “snapshots”.
- ▶ The Crypto Analytics Tool client is a workstation program that accesses the Crypto Analytics Tool database by using a JDBC connection to generate the reports.

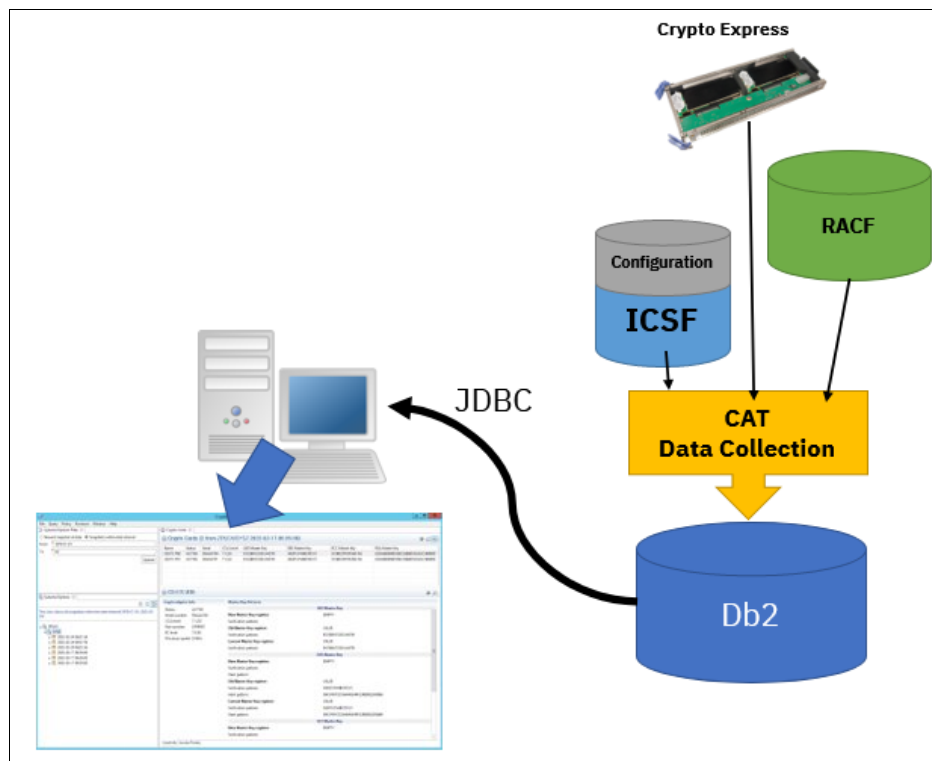


Figure 5-6 CAT architectural overview

5.4.2 Reported elements

Whenever you are running the z/OS data collection, the Db2 tables are populated with the results of the data collection, called *snapshots*. The following elements are reported by CAT in the snapshots:

- ▶ ICSF configuration

The ICSF configuration report provides basic information about the ICSF status at the time of the snapshot (sysplex mode, initialization status, CKDS format, and so on). The report also provides the status of runtime options (such as special secure mode and PCF coexistence), the ICSF policies, exit routines, and UDX services.

- ▶ Protected verbs and utilities

The protected verbs and utilities report lists all the ICSF services and extracts from RACF the profiles that are protecting these services along with the access list to the profiles.

- ▶ Crypto Express

This report provides a list of adapters that are assigned to the LPAR where the snapshot was taken, along with the status of the master keys. The report also provides the access points (ACPs) setup.

- ▶ Key data sets (xKDS)

The Key data sets report provides the name of the xKDS along with the status of their RACF protection. It also includes the Masters Keys verification patterns.

- ▶ Keys

For each type of key (DES, RSA, AES, and so), this report lists all the keys (with a search option) and their type, size, metadata, and so on. For each key, their RACF protection profiles can be displayed along with the options for the ICSF segment, such as SYMCPACFWRAP.

- ▶ RACF

The RACF report provides the list of all the RACF profiles in the classes that are related to cryptography, such as CRYPTOZ and CSFSERV. The report also provides the list of users and groups with access to these profiles, along with the certificates and key rings that are present in RACF.

5.4.3 Monitoring functions

CAT provides the following monitoring functions:

- ▶ Queries

In CAT Monitor, predefined queries can be performed. Two types of queries are available: Queries that compare two selected snapshots, and queries that generate a report for a selected snapshot.

For example, by using the comparison function, the comparison report highlights the new keys that are found in the keystore if you compare two different snapshots after a key generation event.

- ▶ Policy check

With the policy check, set of policy rules can be specified that can be used to analyze the extracted data and flag whether the objects are compliant or noncompliant according to the policy rules. The set of policy rules can be tailored according to your own policy.

5.4.4 Crypto Analytics Tool use case

In this use case, we see how you can use CAT to generate a policy report to identify non-Quantum-safe keys in your ICSF keystore. For example, analyzing our AES keys that are stored in the ICSF CKDS and report any anomaly, such as a weaker AES 128 key.

For this example, it is assumed that the CAT z/OS data collection component is installed and that the data collection is run at a regular interval.

The CAT Monitor was installed on a workstation, the JDBC license was copied into the <CATMonitor>\configuration\license directory, and the Db2 connection information is provided.

First, we activate the default policy, verify the content of the policy for AES keys and then, apply it to our AES 256 keys.

5.4.5 Activating the policy

We enable the built-in Policy. On the workstation where CAT is installed by selecting **Window → Preferences**.

By default, the built-in policy is not activated. To activate it, select the policy and click **Set Active** and then, **Apply** (see Figure 5-7).

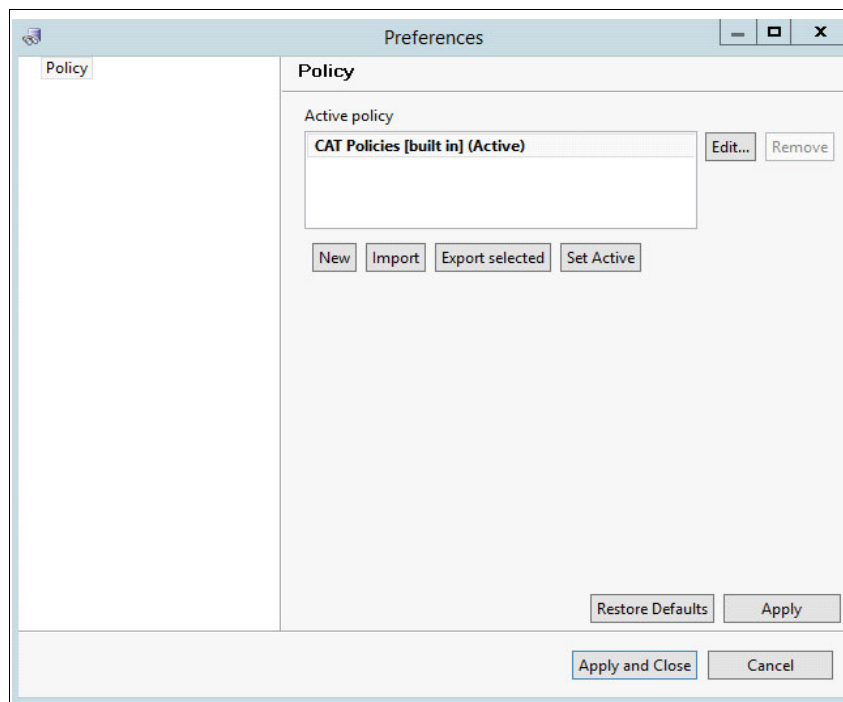


Figure 5-7 CAT Policy Activation

5.4.6 Checking the policy

To verify the content of the policy, select the policy and then, click **Edit**.

The policy editor is displayed (see Figure 5-8), which includes the name of the policy, a description, and a tab for each of the cryptographic elements where a policy can be applied.

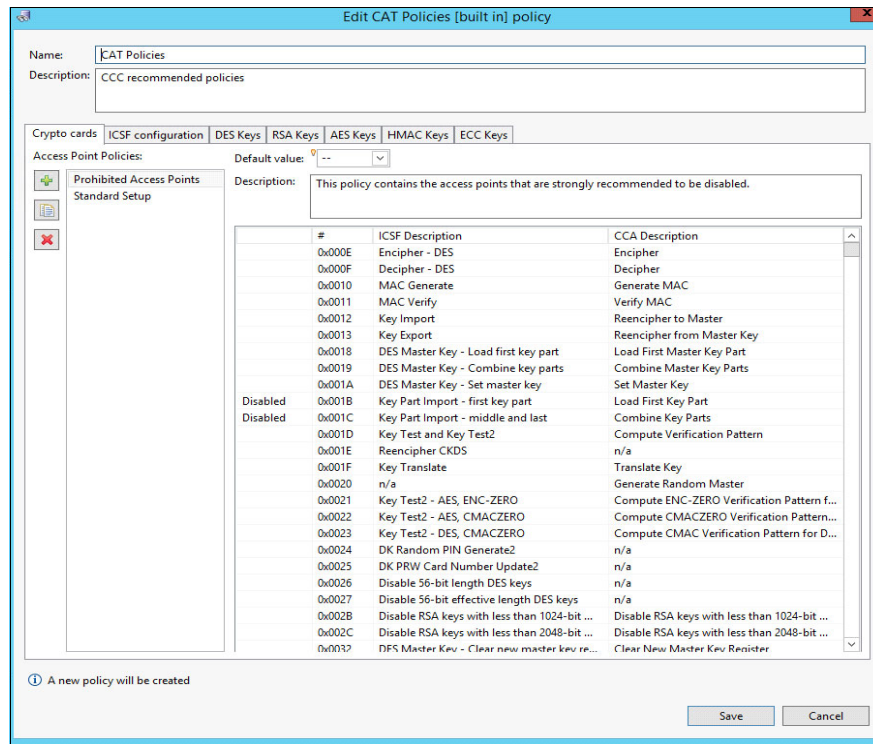


Figure 5-8 CAT Policy Editor

If we select the **AES Keys** tab, we can see that the default policy reports any AES128 key that is created after 2004-01-01, any AES192 key created after 2011-01-01, and so on.

As shown in Figure 5-9, the policy also reports any keys with identical Key Check Value (KCV); that is, those key labels have the same key value.

The screenshot shows a window titled "Edit CAT Policies [built in] policy". It contains the following elements:

- Name:** CAT Policies
- Description:** CCC recommended policies
- Tabs:** Crypto cards, ICSF configuration, DES Keys, RSA Keys, AES Keys (selected), HMAC Keys, ECC Keys
- Same KCV:** Warning (dropdown)
- Key length policies:**

Key length	AES created after	Warning
128	2004-01-01	Warning
192	2011-01-01	Warning
256	2031-01-01	Warning
UNKNOWN	2031-01-01	Warning
- Footer:** ⓘ A new policy will be created, Save, Cancel

Figure 5-9 AES Key Length Policies

Exit the Preference dialog by clicking **Cancel** twice.

5.4.7 Applying the policy to a snapshot

When back in CAT main window, select and expand a snapshot in the Systems Explorer frame.

In the ICSF section, the types of keys that are present in the key data sets are listed. As shown in Figure 5-10 on page 87, we right-clicked **AES Keys** and then, selected **Policy** → **Verify AES Keys**.

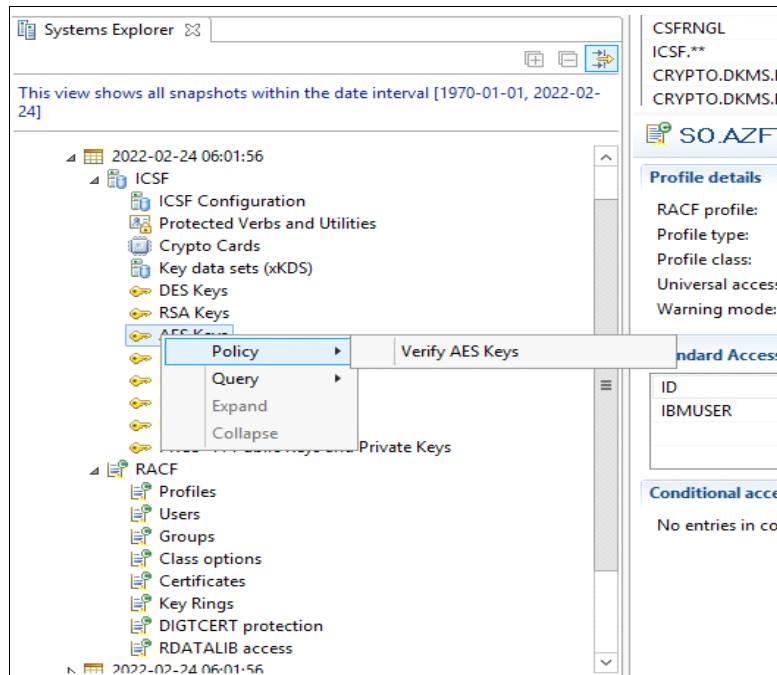


Figure 5-10 Running the AES Key Policy

The Policy Check report is displayed. In Figure 5-11, the Policy Check Report is highlighting that some noncompliant AES keys were found in our keystore.

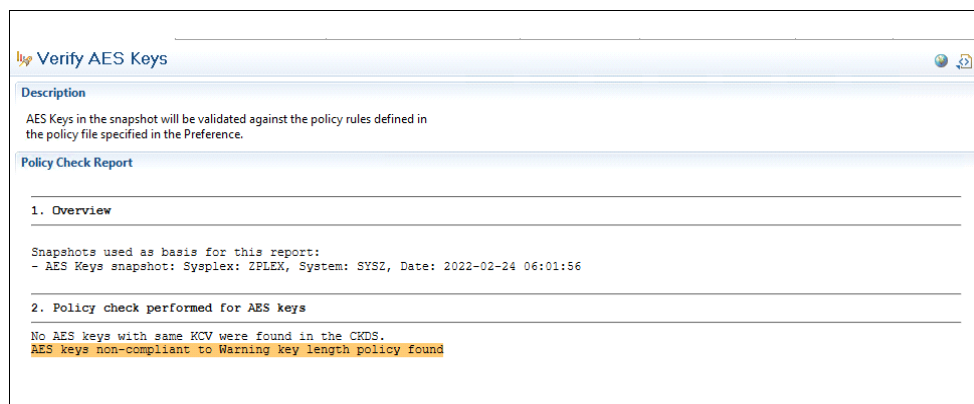


Figure 5-11 CAT Monitor AES Policy Check Report

AES keys non-compliant to Warning key length policy (1 from ZPLEX/SYSZ 2022-02-24 06:01:56)

KCV	Key Label	Key Size	Key Type	Key Creation Time	Key Update Time
BD1B248F66D3A4E7	REDPAPER.AES128.KEY	128	AESDATA	2022-02-24 17:56:47.77	1900-01-01 01:00:00.0

REDPAPER.AES128.KEY

Key info

Algorithm:	AES	Key type:	AESDATA
Creation time:	2022-02-24 17:56:47.77	Key type (in CKDS):	DATA
Update time:	1900-01-01 01:00:00.0	Version:	04
Wrapping method:		Wrapping algorithm:	
Key label:	Internal token	Key size:	128
Key material state:		Key verification pattern (KVP) type:	

Details

KCV:	BD1B248F66D3A4E7
KCV method:	SHA-256
LRC check sum:	28
Key verification pattern (KVP) value:	

Duplicate keys

No other keys with same key value

Key Info | RACF protection | ICSF segment

5.5 Using IBM z/OS Encryption Readiness Technology

IBM zERT is a communications server feature that provides information about the cryptographic network protection state of TCP/IP and Enterprise Extender connections that end on a z/OS system. It also reports their usage in SMF records.

With IBM zERT Network Analyzer (see Figure 5-13), a web-based GUI runs under z/OSMF. z/OS network security administrators can analyze and report on the data that is reported in zERT Summary records (SMF type 119 subtype 12).

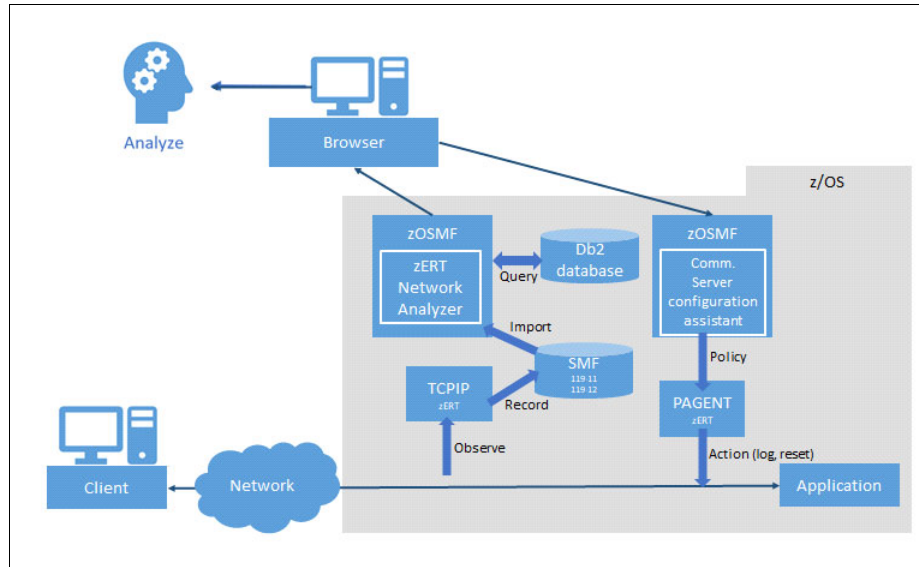


Figure 5-13 zERT Process

Note: At least Db2 for z/OS V11 is required as the database repository for IBM zERT Network Analyzer.

With z/OS 2.5 and zERT Policy Enforcement, you can define required network security policy, including the encryption algorithm in use and then, direct the TCP/IP stack to take specific actions for connections that do not meet that defined policy through the policy agent (PAGENT).

5.5.1 Enabling zERT for zERT Network Analyzer

To generate the zERT summary records, the following parameters are required in the TCP/IP configuration profile:

- ▶ ZERT AGGREGATION in the GLOBALCONFIG section
- ▶ TYPE119 ZERTSUMMARY in the SMFCONFIG section

Also, the z/OS SMF configuration parmlib member should enable the collection of the SMF type 119 records.

5.5.2 Using IBM zERT Network Analyzer

In this section, we demonstrate how zERT network analyzer can be used during the cryptographic inventory step to provide encryption algorithms data for z/OS Communications Server.

Configuration tasks overview

Before IBM zERT Network Analyzer is used, the following configuration tasks are required:

- ▶ Authorize the user IDs to use the IBM zERT Network Analyzer (see `SYS1.SAMPLIB(IZUNASEC)`).
- ▶ Work with your Db2 for z/OS database administrators to create the Db2 database objects and connect IBM zERT Network Analyzer to the Db2 database.

Populating IBM zERT Network Analyzer database

To perform this task, you need cataloged SMF dump data sets with the SMF record type 119 and subtype 12, zERT aggregation records. The z/OSMF task (usually user IZUSVR) must be authorized to read the SMF dump data sets.

Complete the following steps:

1. In the main IBM zERT Network Analyzer page, select **Data Management** → **Import SMF Data** → **Add data set**. Add all the required SMF dumps data sets.
2. Select all of the data sets that you want to import in the database and then, click **Import Selected**. Then, confirm that you want to import the selected data sets (see Figure 5-14).

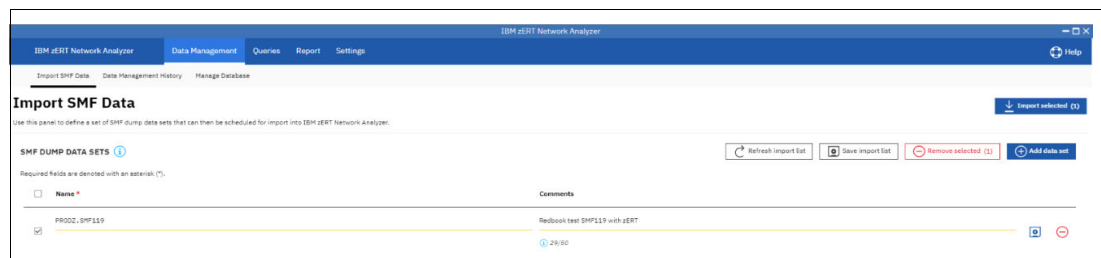


Figure 5-14 IBM zERT Network Analyzer Import SMD Data

The import operation is asynchronous, and the completion of the import can be checked in the Data Management History window by reviewing the Status column (see Figure 5-15). The task can be selected to expand to a detailed view of the import operation (number of records added, duplicate, and ignored).

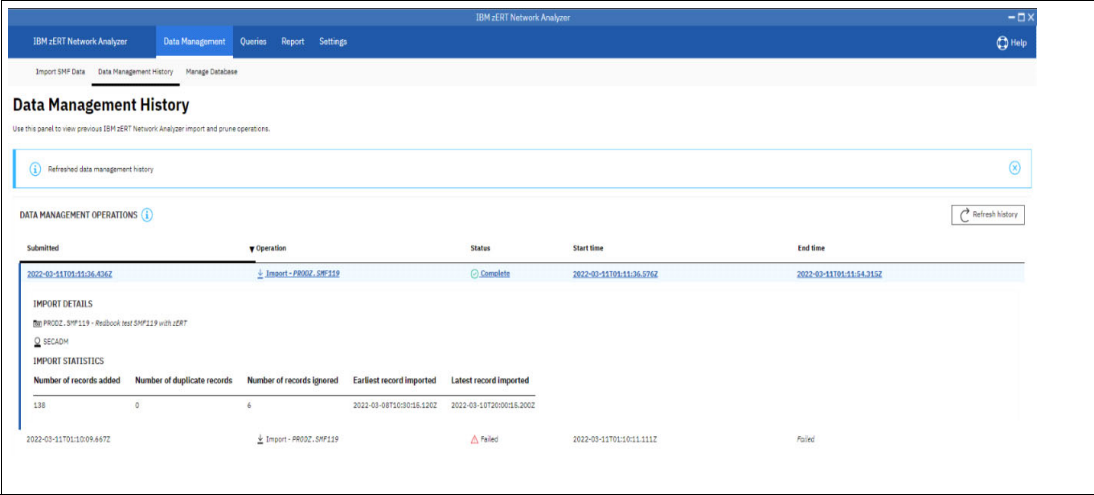


Figure 5-15 IBM zERT Network Analyzer SMF import details

Building your first query

Now that the SMF data is imported into the Db2 database, you can build your first query. Complete the following steps:

1. In the main IBM zERT Network Analyzer page (see Figure 5-16), select **Queries** → **New query**. Here, you must provide a query name and (optionally) a description for the query.

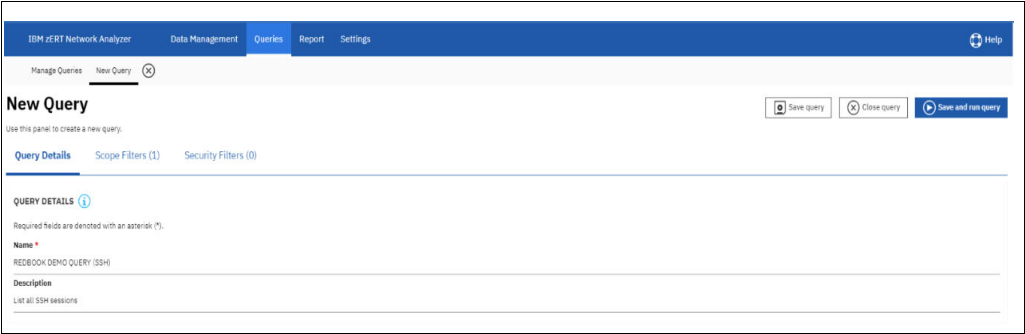


Figure 5-16 IBM zERT Network Analyzer creating a new query

By default, the query retrieves all available SMF records, and reports on all of the data that is available in the Db2 database.

However, to limit the output of the query and select more valuable information, you can add a scope filter. This filter can limit the output to a specific data range (such as, the last 30 days), the sysplex/systems/TCP/IP stack, the TCP or Enterprise Extender IP, ports, and client IP (see Figure 5-17).

IBM zERT Network Analyzer
Data Management
Queries
Report
Settings
Help

Manage Queries
New Query

New Query

Use this panel to create a new query.

Save query
Close query
Save and run query

Query Details
Scope Filters (1)
Security Filters (0)

Time and Date
☐ Date Range

Systems
☒ Systems

Network
☐ TCP Endpoints
☐ EE Endpoints

SYSTEMS

Sysplex	System	TCP/IP stack	
ZPLEX	SYS2	TCP/IP	Remove filter
			Add system

Figure 5-17 IBM zERT Network Analyzer query scope filter

You can limit the output of the query by selecting **Security Filters**. In the Security filter window, you can limit the output of the query to specific security traffic (unprotected, IPsec, TLS, and SSH). Within a security traffic, such as TLS, you can limit the output to specific algorithms (see Figure 5-18).

IBM xERT Network Analyzer

Data Management

Queries

Report

Settings

Manage Queries

New Query

New Query

Use this panel to create a new query.

Query Details

Scope Filters (1)

Security Filters (1)

Unprotected* Traffic

☐ All traffic with no recognized cryptographic protection

IPSec

☐ All IPSec protected traffic

☐ IPSec symmetric encryption algorithm
☐ IPSec message authentication algorithm
☐ IPSec certificate digital signature algorithm
☐ IPSec certificate asymmetric key length
☐ IPSec key exchange algorithm

TLS

☐ All TLS protected traffic

☐ TLS protocol version
☐ TLS symmetric encryption algorithm
☐ TLS message authentication algorithm
☐ TLS digital signature algorithm
☐ TLS certificate asymmetric key length
☐ TLS key exchange algorithm

SSH

☐ All SSH protected traffic

☐ SSH protocol version
☐ SSH symmetric encryption algorithm
☐ SSH message authentication algorithm
☐ SSH key type
☐ SSH key length
☒ SSH key exchange algorithm

SSH KEY EXCHANGE ALGORITHM ⓘ

☐ Unknown
☐ None
☐ Diffie-Hellman-group-exchange-sha256
☐ Diffie-Hellman-group-exchange-sha1
☐ Diffie-Hellman-group14-sha1
☐ Diffie-Hellman-group1-sha1
☒ ECDH-sha2-nistp256

☒ ECDH-sha2-nistp256
☒ ECDH-sha2-nistp192
☐ GSS-GRP01-sha1
☐ GSS-GRP016-sha1
☐ GSS-GEX-sha1
☐ ECDHE-sha2
☐ GSS-?

☐ RSA1024-sha1
☐ RSA2048-sha256
☐ Diffie-Hellman-group14-sha256
☐ Diffie-Hellman-group16-sha512
☐ Diffie-Hellman-group19-sha512
☒ Curve 25519-sha256

Save query

Close query

Figure 5-18 IBM zERT Network Analyzer Security session filters

2. After your query definition is complete, click **Save and run query**. After confirmation, the query runs and the result is available in the Report window.

Viewing the query result

The query results are available in the Report window (see Figure 5-19).

The screenshot shows the IBM zERT Network Analyzer interface. The top navigation bar includes 'Data Management', 'Queries', 'Report', and 'Settings'. The 'Report' tab is active, displaying a report titled 'Report: REDBOOK DEMO QUERY (SSH)'. Below the title, there are tabs for 'TCP Server Traffic', 'TCP Client Traffic', and 'EE Peer Traffic'. The main table displays query results with columns: Sysplex, System, Stack, Server IP, Server Port, User ID, Job Name, Unprotected* Total Conns, IPsec Total Conns, SSH Total Conns, and TLS Total Conns. The data row shows: ZPLEX, SYSZ, TCP/IP, 10.0.0.216, 22, START1, SSM03, 0, 0, 1, 0. A 'Close report' button and an 'Export to CSV' button are visible in the top right corner.

Sysplex	System	Stack	Server IP	Server Port	User ID	Job Name	Unprotected* Total Conns	IPsec Total Conns	SSH Total Conns	TLS Total Conns
ZPLEX	SYSZ	TCP/IP	10.0.0.216	22	START1	SSM03	0	0	1	0

Figure 5-19 IBM zERT Network Analyzer query result

The query result features one summary line, with the Sysplex, System, Stack, and Server IP along with the ports, jobname, and summary information about the type of session that was reported (unprotected, IPsec, SSH, and TLS).

You can expand the results, and get more information by clicking the query result line.

IBM zERT Network Analyzer shows the list of Clients IP along with another summary of the sessions. You can get more information about the sessions for a specific client or all the clients by selecting the IP addresses that you want to analyze and then, clicking **View security session details** (see Figure 5-20).

The screenshot shows the 'CLIENT DETAILS FOR SERVER 10.0.0.216:22' section. It includes a table with columns: Client IP, Unprotected* Total Conns, IPsec Total Conns, SSH Total Conns, and TLS Total Conns. The data row shows: 10.0.0.240, 0, 0, 1, 0. A 'View security session details' button is visible in the top right corner.

Client IP	Unprotected* Total Conns	IPsec Total Conns	SSH Total Conns	TLS Total Conns
10.0.0.240	0	0	1	0

Figure 5-20 IBM zERT Network Analyzer client details

The report displays (see Figure 5-21). For each client IP selected, the details about the security are provided (Protocol version, Key Exchange Algorithm, and so on).

The screenshot shows the 'SECURITY SESSION DETAILS FOR SERVER 10.0.0.216:22' section. It includes a table with columns: Client IP, Protocol Version, Key Exchange Alg, Symm Encryption Alg In, Symm Encryption Alg Out, Message Auth Alg In, Message Auth Alg Out, Auth Method, Server Key Length, and Client Key Length. The data row shows: 10.0.0.240, Protocol version 2, Curve 25519-DHA256, AES CTR 256, AES CTR 256, HMAC-SHA2-256, HMAC-SHA2-256, Password, 0, 0. A 'View client details' button is visible in the top right corner.

Client IP	Protocol Version	Key Exchange Alg	Symm Encryption Alg In	Symm Encryption Alg Out	Message Auth Alg In	Message Auth Alg Out	Auth Method	Server Key Length	Client Key Length
10.0.0.240	Protocol version 2	Curve 25519-DHA256	AES CTR 256	AES CTR 256	HMAC-SHA2-256	HMAC-SHA2-256	Password	0	0

Figure 5-21 IBM zERT Network Analyzer security session details

All the query results are exportable, and can be used in spreadsheet by clicking **Export to CSV**.

Creating your own data-in-transit cryptographic inventory

From the previous example, we discovered that we can create specific targeted reports about specific types of security sessions and algorithms by using the IBM zERT Network Analyzer.

Then, you can build a cryptographic inventory for your data-in-transit, with specific attributes, such as the clients/servers you are targeting, the protocols or cryptographic algorithms (which is useful to prepare a transition for specific applications/client-servers in the enterprise).

5.5.3 Monitoring data in-transit by using zERT

With z/OS 2.5, a feature called zERT Enforcement Policy was introduced. With this feature, you can now define a policy with filters that is based on addresses, ports, jobname, encryption algorithm, and ciphers. Then, you can take actions if the connection is not “in policy”. The actions can be logging only (SMF, syslogd, and console) or resetting the TCP/IP connection. The policy is enforced by the Policy Agent address space (PAGENT).

Creating a policy

To create a zERT Enforcement Policy, it is recommended to use, the z/OSMF Network Configuration assistant (see Figure 5-22) as is done with the others policy agent-based policies (such as AT/TLS and IPsec).

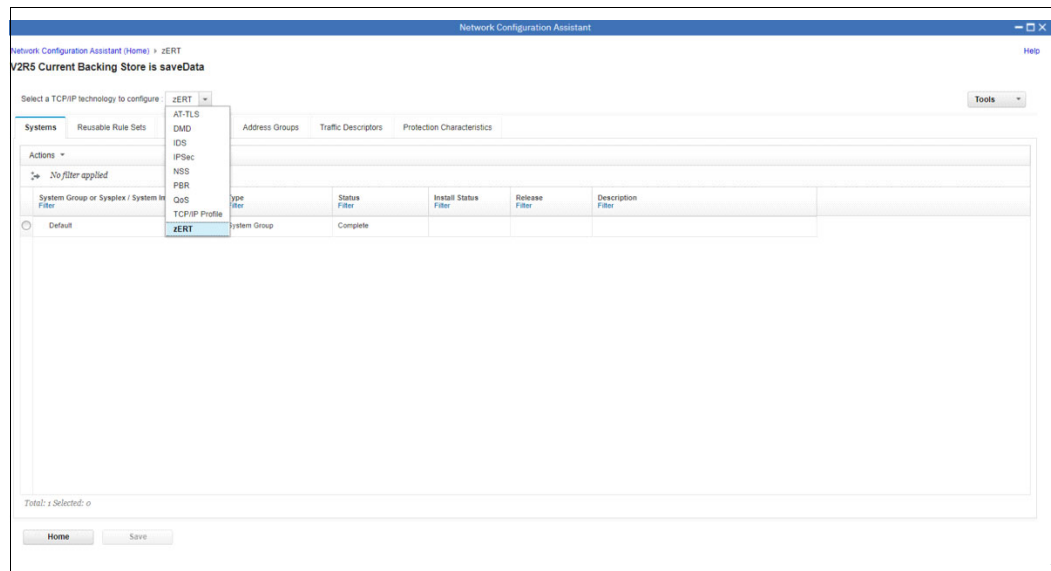


Figure 5-22 Main page of z/OS Configuration Assistant

In the policy, you can define multiple criteria that the connection needs match to trigger the policy. Then, in the actions, you define what occurs if such connection is established.

For example, you can reset a nonsecure connection and disconnect the client so that no information transits in this nonsecure connection.

In our environment, TN3270clear connection requests coming from IP address 10.0.0.111 are not permitted (see Figure 5-23). Therefore, the client immediately disconnects after reporting the information in the z/OS log.

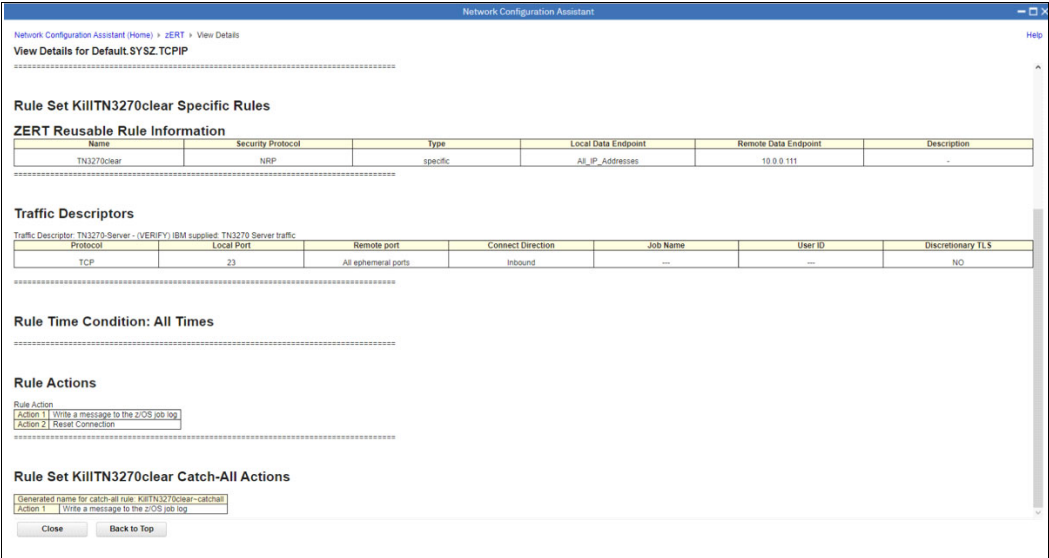


Figure 5-23 zERT Rule information

After activating the policy through the policy agent, we can see in the PAGENT log (refer to Example 5-8) that message EZZ8771I is issued. We also see that the TN3270 client with an IP address of 10.0.0.111 starts a nonsecure connection, which is immediately reported and disconnected through a reset of the connection (message EZZ8562I).

Example 5-8 PAGENT Log

```

EZZ8771I PAGENT CONFIG POLICY PROCESSING COMPLETE FOR TCPIP : TTLS
EZZ8771I PAGENT CONFIG POLICY PROCESSING COMPLETE FOR TCPIP : ZERT
EZD1289I TCPIP ICSF SERVICES ARE CURRENTLY AVAILABLE FOR AT-TLS GROUP
AZFGroupAction1
EZZ6035I TN3270 DEBUG CONN  DETAIL 373
  IP..PORT: 10.0.0.111..53854
  CONN: 000056FA  LU: SYSZTCP8 MOD: EZBTTRCV
  RCODE: 1001-01  Client disconnected from the connection.
  PARM1: 00000000 PARM2: 00000000 PARM3: 00000000
EZZ6034I TN3270 CONN 000056FA LU SYSZTCP8 SESS DROP  CLNTDISC 374
  IP..PORT: 10.0.0.111..53854
IKT100I USERID              CANCELED DUE TO UNCONDITIONAL LOGOFF
IKT122I IPADDR..PORT 10.0.0.111..53854
EZZ6034I TN3270 CONN 000056FA LU SYSZTCP8 CONN DROP  CLNTDISC 376
  IP..PORT: 10.0.0.111..53854
EZZ6034I TN3270 CONN 0000571C LU **N/A**  ACCEPTED      23 378
  IP..PORT: 10.0.0.111..55623
EZZ8562I CONN RESET BY ZERT POLICY 379
EZZ8552I STACK= TCPIP CONNID= 0000571C CONNDIR= INBOUND
EZZ8553I LOCALIPADDR= 10.0.0.216 LOCALPORT= 23
EZZ8554I REMOTEIPADDR= 10.0.0.111 REMOTEPORT= 55623
EZZ8555I TRANSPROTO= TCP JOBNAME= TN3270 USERID= TCPIP
EZZ8556I SECPROTO= NONE SECPROTOVERSION= N/A
EZZ8560I RULE= TN3270clear
EZZ8561I ACTION= Reset_Console

```

This example shows a simple policy, but during your quantum-safe journey, you can define rules that are based on these encryption algorithms to prevent (or report real-time) connections that use non-quantum-safe encryption algorithms.



Deploying quantum-safe capabilities

Now that your cryptographic inventory is created (as discussed in Chapter 5, “Creating a cryptographic inventory” on page 71), the preparation and planning can begin for the replacement of weak symmetric keys and public key algorithms. The algorithms and protocols at risk are discussed in “Cryptographic vulnerabilities possible with quantum computers” on page 9.

Adopting and implementing agreed upon quantum-safe standards, algorithms, and protocols in cryptographic systems helps protect against quantum computer and conventional computer attacks.

This chapter includes the following topics:

- ▶ 6.1, “Quantum-safe algorithm artifacts” on page 98
- ▶ 6.2, “Converting your PKDS to KDSRL format” on page 99
- ▶ 6.3, “Ensuring the environment is ready” on page 101
- ▶ 6.4, “Quantum-safe key generation” on page 102
- ▶ 6.5, “Quantum-safe encryption” on page 105
- ▶ 6.6, “Quantum-safe digital signatures” on page 107
- ▶ 6.7, “Quantum-safe hybrid key exchange” on page 113
- ▶ 6.8, “Quantum-safe hashing” on page 117
- ▶ 6.9, “Validating your quantum-safe transition” on page 118

6.1 Quantum-safe algorithm artifacts

As you transition your cryptographic infrastructure to quantum-safe algorithms, it is important to understand some of the differences in artifact sizes between quantum-safe algorithms and traditional public key cryptography. It also is important to understand the supported quantum-safe algorithm object identifiers.

Quantum-safe algorithm (QSA) keys and signatures are much larger and might require changes in your environment. CCA QSA, RSA, and Elliptic Curve Cryptography (ECC) keys are compared in Table 6-1. The token size does not include other sections (such as private key name). The PKCS #11 key objects and signatures are of comparable size to the CCA key tokens.

Table 6-1 CCA public key token and signature sizes

Algorithm	Public key token size (bytes)	Private key token size (bytes)	Signature size (bytes)
RSA CRT 4096	1104	2504	512
ECC Edwards 448	79	323	114
CRYSTALS-Dilithium 6,5 Round 3	1984	6128	3293
CRYSTALS-Dilithium 8,7 Round 3	2624	7632	4595

The supported quantum-safe algorithm object identifiers (OIDs) on IBM z15 and IBM z16 with Crypto Express7S and Crypto Express8S features are listed in Table 6-2.

Table 6-2 Supported quantum-safe algorithm object identifiers

Algorithm	Algorithm strength/version ^a	Object identifier
CRYSTALS-Dilithium	CRYSTALS-Dilithium 6,5 Round 2	1.3.6.1.4.1.2.267.1.6.5
	CRYSTALS-Dilithium 6,5 Round 3	1.3.6.1.4.1.2.267.7.6.5
	CRYSTALS-Dilithium 8,7 Round 2	1.3.6.1.4.1.2.267.1.8.7
	CRYSTALS-Dilithium 8,7 Round 3	1.3.6.1.4.1.2.267.7.8.7
CRYSTALS-Kyber	CRYSTALS-Kyber 1024 Round 2	1.3.6.1.4.1.2.267.5.4.4

a. Crypto Express7S features support CRYSTALS-Dilithium 6,5 Round 2 only

For more information about the supported quantum-safe OIDs, see *ICSF Application Programmer's Guide*, SC14-7508.

For more information about each quantum-safe algorithm, see the following web pages:

- [CRYSTALS-Dilithium](#)
- [CRYSTALS-Kyber](#)

6.2 Converting your PKDS to KDSRL format

If you plan to store CCA QSA key tokens in your ICSF Public Key Data Set (PKDS), you must be on ICSF FMID HCR77D2 and have a large common record format (KDSRL) PKDS. KDSRL format supports all asymmetric key tokens and metadata. It also allows key usage tracking, if configured. KDSRL format increases the logical record length (LRECL) of the PKDS 3800 to 32756.

ICSF provides a utility to convert a KDSR format PKDS to KDSRL format by using the ICSF panes.

Complete the following steps to convert a PKDS to KDSRL format by using the ICSF panes:

1. On the ICSF Primary menu (see Example 6-1), select option **2, KDS MANAGEMENT** and then, press **Enter**.

Example 6-1 ICSF Primary menu

```
HCR77D2 ----- Integrated Cryptographic
System Name: SY1                      Crypto Domain: 0
Enter the number of the desired option.

1  COPROCESSOR MGMT - Management of Cryptographic Coprocessors
2  KDS MANAGEMENT  - Master key set or change, KDS Processing
3  OPSTAT           - Installation options
4  ADMINCNTL        - Administrative Control Functions
5  UTILITY          - ICSF Utilities
6  PPINIT           - Pass Phrase Master Key/KDS Initialization
7  TKE              - TKE PKA Direct Key Load
8  KGUP             - Key Generator Utility processes
9  UDX MGMT         - Management of User Defined Extensions

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disclosure restricted by GSA ADP Schedule Contract with IBM Corp.

Press ENTER to go to the selected option.
Press END   to exit to the previous menu.
OPTION ==>
```

2. On the Key Data Set Management pane (see Example 6-2), select option **2, PKDS MANAGEMENT** and then, press **Enter**.

Example 6-2 ICSF key data set management

```
----- ICSF - Key Data Set Management -----

Enter the number of the desired option.

1  CKDS MANAGEMENT - Perform Cryptographic Key Data Set (CKDS)
                        functions including master key management
2  PKDS MANAGEMENT - Perform Public Key Data Set (PKDS)
                        functions including master key management
3  TKDS MANAGEMENT - Perform PKCS #11 Token Data Set (TKDS)
                        functions including master key management
4  SET MK           - Set master keys
```

Press ENTER to go to the selected option.
Press END to exit to the previous menu.

3. On the PKDS Management pane (see Example 6-3), select option **6, COORDINATED PKDS CONVERSION** and then, press **Enter**.

Example 6-3 PKDS Management

----- ICSF - PKDS Management -----

Enter the number of the desired option.

- 1 PKDS OPERATIONS - Initialize a PKDS, activate a different PKDS, (Refresh), or update the header of a PKDS and make it active
- 2 REENCIPHER PKDS - Reencipher the PKDS
- 3 CHANGE ASYM MK - Change an asymmetric master key and activate the reenciphered PKDS
- 4 COORDINATED PKDS REFRESH - Perform a coordinated PKDS refresh
- 5 COORDINATED PKDS CHANGE MK - Perform a coordinated PKDS change master key
- 6 COORDINATED PKDS CONVERSION - Convert the PKDS to KDSR/L record format
- 7 PKDS KEY CHECK - Check key tokens in the active PKDS for format errors

Press ENTER to go to the selected option.
Press END to exit to the previous menu.

4. On the Coordinated KDS conversion pane (see Example 6-4), enter the new KDS name and then, press **Enter**.

Example 6-4 Coordinated KDS conversion

----- ICSF - Coordinated KDS conversion -----

To perform a coordinated KDS conversion, enter the KDS names below and optionally select the rename option.

KDS Type ==> PKDS

Active KDS ==> 'SYS1.PKDS.KDSR'

New KDS ==> 'SYS1.PKDS.KDSRL'

Rename Active to Archived and New to Active (Y/N) ==> N

Archived KDS ==>

Create a backup of the converted KDS (Y/N) ==> N

Backup KDS ==>

Press ENTER to perform a coordinated KDS conversion.
Press END to exit to the previous menu.

After converting your PKDS to KDSRL format, you can confirm the change by using the **D ICSF,KDS** command. The output is shown in Example 6-5.

Example 6-5 D ICSF, KDS output

```

SY1          d icsf,kds
SY1          CSFM668I 14.28.13 ICSF KDS 875
  CKDS  SYS1.CKDS.KDSR
    FORMAT=KDSR      COMM LVL=3  SYSPLEX=Y  MKVPs=DES AES
    DES MKVP date=Unknown
    AES MKVP date=Unknown
  PKDS  SYS1.PKDS.KDSRL
    FORMAT=KDSRL      COMM LVL=3  SYSPLEX=Y  MKVPs=RSA ECC
    RSA MKVP date=Unknown
    ECC MKVP date=Unknown
  TKDS  SYS1.TKDS.KDSRL
    FORMAT=KDSRL      COMM LVL=3  SYSPLEX=Y  MKVPs=P11
    P11 MKVP date=Unknown

```

6.3 Ensuring the environment is ready

The examples in the subsequent sections assume that all the necessary hardware and software is installed. Review the information in this section before deploying the quantum-safe capabilities.

The following general prerequisites must be met:

- ▶ ICSF FMID HCR77D2 or later is installed with the latest service level
- ▶ z/OS 2.5 or later is installed
- ▶ Running on IBM z15 or later
- ▶ Crypto Express7S or later is installed and configured
- ▶ CPACF feature code 3863 is enabled

For the CCA examples, our environment featured the following components:

- ▶ z/OS 2.5 installed and running on an IBM z16.
- ▶ ICSF FMID HCR77D2 with the latest service level applied.
- ▶ The CKDS and PKDS are allocated and in the correct format:
 - The CKDS is recommended to be in KDSRL format.
 - The PKDS must be in KDSRL format. For more information, see “Converting your PKDS to KDSRL format” on page 99.
- ▶ Two Crypto Express8S (CEX8C) were installed and configured as CCA coprocessors (for more information, see *IBM z16 Configuration Setup*, SG24-8960).
- ▶ Feature Code (FC) 3863 was enabled for CPACF use.
- ▶ The AES master key was set and active in each CEX8C (CCA coprocessor) and initialized in the CKDS header. The Master Key Verification Pattern must be the same across your environment.

If you are converting ciphertext that is encrypted with secure CCA DES keys, you must have the DES master key set and active in each CEX8C coprocessor and initialized in the CKDS header. The Master Key Verification Pattern *must* be the same across your environment.

CCA CRYSTALS-Dilithium and CRYSTALS-Kyber key operations require that the ECC master key be set and active in each CEX8C coprocessor and initialized in the PKDS header. The Master Key Verification Pattern must be the same across your environment.

For the PKCS #11 examples, we made the following changes to our environment:

- ▶ The TKDS was allocated. A TKDS is not required if session objects are used.
- ▶ For secure key operations:
 - Two Crypto Express8 (CEX8P) were installed and configured as Enterprise PKCS #11 (EP11) coprocessor.
 - The EP11 master key was set and active in each CEX8P and initialized in the TKDS header. The Master Key Verification Pattern must be the same across your environment. A TKE is required to set the EP11 master key.

Note: PKCS #11 hybrid key-exchange can be done in hardware only.

For more information about allocating ICSF Key Data Sets and entering and activating ICSF master keys, see *z/OS ICSF Administrator's Guide*, z/OS, SC14-7506.

For more information about the IBM Z cryptographic stack, see 4.1, “IBM Z cryptographic components overview” on page 48.

6.4 Quantum-safe key generation

This section describes generating cover keys for AES 256, CRYSTALS-Dilithium, and CRYSTALS-Kyber algorithms by using ICSF services.

AES 256, CRYSTALS-Dilithium, and CRYSTALS-Kyber are proven to be resistant to attacks from a powerful quantum computer. They also are ideal candidates when transitioning your application that is identified in your cryptographic inventory.

The PKCS #11 sample assumes that your environment is running with a specified ICSF TKDS. For more information about allocating and initializing a TKDS, see *ICSF System's Programmer's Guide*, SC14-7507.

6.4.1 Generating an AES 256-bit key by using ICSF CCA services

Generating a secure AES 256-bit CIPHER CCA key token can be done by using the Key Token Build2 (CSNBKTB2 and CSNEKTB2) and Key Generate2 (CSNBKGN2 and CSNEKGN2) ICSF services.

To generate a CCA AES 256-bit key, complete the following steps:

1. Build a skeleton token by using CSNBKTB2 with the correct key usage and key management bits specified. Ensure key type CIPHER is specified.
2. Pass the created skeleton token from CSNBKTB2 to CSNBKGN2 and specify the AES and OP rules.

The secure AES 256-bit CCA key token is generated and can be written to the CKDS with the CKDS Key Record Create2 (CSNBKRC2 and CSNEKRC2) service.

For more information about a sample REXX program that showcases steps 1 and 2, see B.1, “CCA AES 256-bit key generation REXX sample” on page 134.

For more information about these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.4.2 Generating an AES 256-bit key by using ICSF PKCS #11 services

Generating a secure AES 256-bit PKCS #11 key object can be done by using the PKCS #11 Generate Secret Key (CSFPGSK and CSFPGSK6) ICSF service.

To generate a secure PKCS #11 AES 256-bit key, complete the following steps:

1. Initialize a PKCS #11 token by using the PKCS #11 Token Record Create (CSFPTRC and CSFPTRC6) service.
2. Call the CSFPGSK service that passes the token handle that was created in step 1. Specify the CKA_CLASS (with a value of CKO_SECRET_KEY) and CKA_KEY_TYPE (with a value of CKK_AES) object attributes in the attribute list.

For more information about contains a sample REXX program that showcases step 2, see B.2, “PKCS #11 AES 256-bit key generation REXX sample” on page 137.

For more information about key object attributes, see *ICSF Writing PKCS #11 Applications guide*, SC14-7510.

6.4.3 Generating CRYSTALS-Dilithium key by using ICSF CCA services

Generating a secure CRYSTALS-Dilithium key pair can be done by using the PKA Key Token Build (CSNDPKB and CSNFPKB) and PKA Key Generate (CSNDPKG and CSNFPKG) ICSF services.

To generate a CRYSTALS-Dilithium key pair, complete the following steps:

1. Build a skeleton token by using CSNDPKB passing the ‘QSA-PAIR’ and ‘U-DIGSIG’ rules. In the Key Value Structure (KVS), specify the algorithm ID and algorithm parameters for CRYSTALS-Dilithium.
2. Pass the created skeleton token from CSNDPKB to CSNDPKG and specify the ‘MASTER’ rule.

The secure CRYSTALS-Dilithium key pair is generated and can be written to the PKDS with the PKDS Key Record Create (CSNDKRC and CSNFKRC) service if the PKDS is in KDSRL format. For more information, see 6.2, “Converting your PKDS to KDSRL format” on page 99.

The CRYSTALS-Dilithium public key optionally can be extracted from the private key token by using the PKA Public Key Extract (CSNDPKX and CSNFPKX) service.

For more information about a sample REXX program that showcases steps 1 and 2, see B.3, “CCA CRYSTALS-Dilithium key pair generation REXX sample” on page 139.

For more information about these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.4.4 Generating CRYSTALS-Dilithium key by using ICSF PKCS #11 services

Generating a secure PKCS #11 CRYSTALS-Dilithium key object can be done by using the PKCS #11 Generate Key Pair (CSFPGKP and CSFPGKP6) ICSF service.

To generate a secure PKCS #11 CRYSTALS-Dilithium key object, complete the following steps:

1. Initialize a PKCS #11 token by using the PKCS #11 Token Record Create (CSFPTRC and CSFPTRC6) service.
2. Call the CSFPGKP service that passes the token handle that was created from step 1. Specify the CKA_IBM_DILITHIUM_MODE object attribute with the DER encoded OID that corresponds to the CRYSTALS-Dilithium strength that is wanted in the public key attribute list.

For more information about a sample REXX program that showcases step 2, see B.4, “PKCS #11 CRYSTALS-Dilithium key pair generation REXX sample” on page 142.

For more information about key object attributes, see *ICSF Writing PKCS #11 Applications Guide*, SC14-7510.

6.4.5 Generating CRYSTALS-Kyber key by using ICSF CCA services

Generating a secure CRYSTALS-Kyber key pair can be done by using the PKA Key Token Build (CSNDPKB and CSNFPKB) and PKA Key Generate (CSNDPKG and CSNFPKG) ICSF services.

To generate a CRYSTALS-Kyber key pair, complete the following steps:

1. Build a skeleton token by using CSNDPKB passing the QSA-PAIR, U-KEYENC, and U-DATENC rules. In the Key Value Structure (KVS), specify the algorithm ID and algorithm parameter for CRYSTALS-Kyber.
2. Pass the created skeleton token from CSNDPKB to CSNDPKG and specify the MASTER rule.

The secure CRYSTALS-Kyber key pair is generated and can be written to the PKDS with the PKDS Key Record Create (CSNDKRC and CSNFKRC) service if the PKDS is in KDSRL format. For more information, see 1.2: Converting your PKDS to KDSRL format.

The CRYSTALS-Kyber public key optionally can be extracted from the private key token by using the PKA Public Key Extract (CSNDPKX and CSNFPKX) service.

For more information about a sample REXX program that showcases steps 1 and 2, see B.5, “CCA CRYSTALS-Kyber key pair generation REXX sample” on page 144.

For more information about these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.4.6 Generating CRYSTALS-Kyber key by using ICSF PKCS #11 services

Generating a secure PKCS #11 CRYSTALS-Kyber key object can be done by using the PKCS #11 Generate Key Pair (CSFPGKP and CSFPGKP6) ICSF service.

To generate a secure PKCS #11 CRYSTALS-Kyber key object, complete the following steps:

1. Initialize a PKCS #11 token by using the PKCS #11 Token Record Create (CSFPTRC and CSFPTRC6) service.
2. Call the CSFPGKP service that passes the token handle that was created from step 1. Specify the CKA_IBM_KYBER_MODE object attribute with the DER encoded OID corresponding to the CRYSTALS-KYBER strength that is wanted in the public key attribute list.

For more information about a sample REXX program that showcases step 2, see B.6, “PKCS #11 CRYSTALS-Kyber key pair generation REXX sample” on page 147.

For more information about key object attributes, see *ICSF Writing PKCS #11 Applications Guide*, SC14-7510.

6.5 Quantum-safe encryption

Data must be encrypted with AES 256-bit keys to ensure its protection from quantum computers running Grover’s algorithm. For more information about the effect Grover’s algorithm has on symmetric key cryptography, see 1.3, “Impact of Shor’s and Grover’s algorithms” on page 7.

The following options are available to protect ciphertext:

- Translate it by decrypting it by using the original key and then, encrypting it with an AES 256-bit key. The clear text is visible only for a short time within the secure cryptographic coprocessor.
- Reencrypt the ciphertext by using an AES 256-bit key without decrypting it first.
- Decrypt it with Symmetric Key Decipher (CSNBSYD or CSNBSYD1 and CSNESYD or CSNESYD1) and reencrypt it with Symmetric Key Encipher (CSNBSYE or CSNBSYE1 and CSNESYE or CSNESYE1). The clear text is visible only for a short time on the host system.

For more information about generating AES 256-bit keys, see 6.4.1, “Generating an AES 256-bit key by using ICSF CCA services” on page 102.

For more information about the use of AES 256-bit keys to translate cipher text from a weaker key (such as DES) to AES 256-bit encryption (option 1 in the previous bulleted list), see 6.4.2, “Generating an AES 256-bit key by using ICSF PKCS #11 services” on page 103.

6.5.1 Translating ciphertext to AES 256-bit encryption by using ICSF CCA services

Translating ciphertext from a weaker algorithm to AES 256-bit can be done by using the Cipher Text Translate2 (CSNBCTT2, CSNBCTT3, CSNECTT2, CSNECTT3) ICSF service.

To translate ciphertext to AES 256-bit encryption, complete the following steps:

1. Generate an AES 256-bit CIPHER key by using the ENCRYPT and C-XLATE key usage bits enabled. For more information, see B.1, “CCA AES 256-bit key generation REXX sample” on page 134.
2. Call the Cipher Text Translate2 service that passes the key that originally encrypted the ciphertext as the `key_identifier_in` and the new AES 256-bit key as the `key_identifier_out`.

The ciphertext is decrypted within the secure cryptographic coprocessor and reencrypted with the AES 256-bit key.

For more information about a sample REXX program that showcases step 2, see C.1, “CCA ciphertext translation REXX sample” on page 152.

For more information about these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.5.2 Translating ciphertext to AES 256-bit encryption by using ICSF PKCS #11 services

Translating ciphertext from a weaker algorithm to AES 256-bit can be done by using the PKCS #11 Secret Key Reencrypt (CSFPSKR and CSFPSKR6) ICSF service.

Note: This translate ciphertext service supports secure secret keys only.

To translate ciphertext over to AES 256-bit encryption, complete the following steps:

1. Generate an AES 256-bit PKCS #11 key object by using the CKA_IBM_SECURE key attribute set to TRUE. For more information, see B.2, “PKCS #11 AES 256-bit key generation REXX sample” on page 137.
2. Call the PKCS #11 Secret Key Reencrypt service that passes the key handle that originally encrypted the ciphertext as the `decrypt_handle` and the new AES 256-bit key handle as the `encrypt_handle`.

The ciphertext is decrypted within the secure cryptographic coprocessor and reencrypted with the AES 256-bit key.

For more information about a sample REXX program that showcases step 2, see C.2, “PKCS #11 ciphertext translation REXX sample” on page 154.

For more information about these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.6 Quantum-safe digital signatures

Digital signatures are used to validate the authenticity and integrity of a message. Digital signatures also add nonrepudiation, which provides indisputable proof of origin for the signed data.

Traditional public key cryptography, such as RSA and ECC, are compromised of a sufficiently powerful quantum computer that is running Shor's algorithm. This process can lead to issues, such as data history manipulation by forging digital signatures. To protect against such issues, it is important to start adopting hybrid signature schemes that combine traditional public key cryptography and quantum-safe algorithms, such as CRYSTALS-Dilithium.

For more information about how organizations can use digital signatures to verify the authenticity of data, see 3.4, "Proof of authorship" on page 42.

This section describes how to digitally sign and verify data by using the CRYSTALS-Dilithium quantum-safe algorithm.

6.6.1 Generating and verifying CRYSTALS-Dilithium digital signature by using ICSF CCA services

To generate and verify a CRYSTALS-Dilithium digital signature, use the Digital Signature Generate (CSNDDSG and CSNFDSG) and Digital Signature Verify (CSNDDSV and CSNFDSV) ICSF services.

To generate a CRYSTALS-Dilithium signature, complete the following steps:

1. Generate a CRYSTALS-Dilithium CCA key token by using the CSNDPKB and CSNDPKG ICSF services. For more information, see 6.4.3, "Generating CRYSTALS-Dilithium key by using ICSF CCA services" on page 103.
2. Call the CSNDDSG service and specify the CRDL-DSA, MESSAGE, and CRDLHASH rules. Pass the CRYSTALS-Dilithium private key token that was generated in step 1.

With a Crypto Express8 CCA coprocessor, the message to be signed can be up to 15000 bytes.

The generated signature is created. The signature size depends on the strength of the specified CRYSTALS-Dilithium key.

To verify a CRYSTALS-Dilithium signature, complete the following steps:

1. Call the PKA Public Key Extract (CSNDPKX and CSNFPKX) service to extract the CRYSTALS-Dilithium public key from the private key token.
2. Call the CSNDDSV service and specify the CRDL-DSA, MESSAGE, and CRDLHASH rules. Pass the CRYSTALS-Dilithium public key token that was extracted in step 1.

With a Crypto Express8 CCA coprocessor, the message to be verified can be up to 15000 bytes.

You receive a 0/0 return/reason code for a successful verification.

For more information about a sample REXX program that showcases a CRYSTALS-Dilithium digital signature generation and verification, see D.1, "CCA CRYSTALS-Dilithium digital signature generation and verification REXX sample" on page 158.

For more information regarding these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.6.2 Generating and verifying CRYSTALS-Dilithium digital signature by using ICSF PKCS #11 services

To generate and verify a CRYSTALS-Dilithium digital signature, use the PKCS #11 Private Key Sign (CSFPPKS and CSFPPKS6) and PKCS #11 Public Key Verify (CSFPPKV and CSFPPKV6) ICSF services.

To generate a CRYSTALS-Dilithium signature, complete the following steps:

1. Generate a CRYSTALS-Dilithium PKCS #11 key pair by using the CSFPGKP ICSF service. Ensure that the private key attribute list contains CKA_SIGN set to TRUE, and the public key attribute list contains CKA_VERIFY set to TRUE. For more information, see 6.4.4, “Generating CRYSTALS-Dilithium key by using ICSF PKCS #11 services” on page 104.
2. Call the CSFPPKS service and specify the LI2 rule. Pass the CRYSTALS-Dilithium private key handle that was generated in step 1.
3. The generated signature is created. The signature size depends on the strength of the specified CRYSTALS-Dilithium key.

To verify a CRYSTALS-Dilithium signature, perform the following steps call the CSFPPKV service and specify the LI2 rule. Pass the CRYSTALS-Dilithium public key handle. Pass the signature to verify and the original message.

A 0/0 return/reason code is returned for a successful verification.

D.2, “PKCS #11 CRYSTALS-Dilithium digital signature generation and verification REXX sample” on page 161 contains a sample REXX program that showcases a CRYSTALS-Dilithium digital signature generation and verification.

For more information about these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.6.3 Using digital signatures to protect SMF records

SMF records are an important part of the auditability to the z/OS platform. For example, SMF records can contain important security-related information, such as RACF processing records (SMF record type 80).

It is important to ensure that these records are never tampered with. SMF digital signature provides a cryptographic means to verify the integrity of the records when log streams are used as the recording media.

In this section, we demonstrate how SMF records digital signature is used to sign SMF records and how to transition to quantum-safe algorithms for that purpose.

Configuring SMF digital signature

An SMF digital signature is based on a token and a key (RSA or ECC). The digital signature can be the same for all the records or specific to a log stream.

Step 1: Creating the token and the associated key pair

We created a PKCS#11 token that is called QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS1. Then, we created a key pair that we bound to this certificate (see Example 6-6).

Example 6-6 Creating and binding a PKCS#11 token and a key pair (RSA)

```
RACDCERT ADDTOKEN(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS1)
RACDCERT GENCERT ID(STCID) SUBJECTSDN(CN('SMF sign cert')) +
WITHLABEL('SMF sign certificate') SIZE(2048) RSA +
NOTAFTER(2023/04/18))
RACDCERT BIND(ID(STCID) LABEL('SMF sign certificate') DEFAULT +
TOKEN(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS1))
```

Step 2: Configuring SMF for digital signature

Example 6-7 shows an SMFPRMxx parmlib member (truncated), which enables SMF digital signature for a log stream IFASMF.ALLSYS.DATA that stores selected z/OS SMF records. Other SMF records that are directed to the default log stream IFASMF.ALLSYS.DEFAULT do not have SMF digital signature processing enabled.

Example 6-7 SMFPRMxx parmlib member enabling SMF digital signature for SMF log streams

```
ACTIVE                /*ACTIVE SMF RECORDING*/
LISTDSN               /* LIST DATA SET STATUS AT IPL*/
NOPROMPT              /*DON'T PROMPT THE OPERATOR */
DEFAULTLSNAME(IFASMF.ALLSYS.DEFAULT,COMPRESS(PERMFIX(32M)))
LSNAME(IFASMF.ALLSYS.DATA,TYPE(0,23,30,42,70:79,80:83,99,113),
        COMPRESS(PERMFIX(64M))
        RECSIGN(HASH(SHA512),SIGNATURE(RSA),
        TOKENNAME(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS1))
)
RECORDING(LOGSTREAM)
...
```

Note that the log stream IFASMF.ALLSYS.DATA must be defined with a MAXBUFSIZE of 65532.

Step 3: Extracting the data from the log stream

When extracting the SMF records from the log streams, we want to ensure that the SMF digital signature is available for post-processing. For this purpose, the NOSIGSTRIP parameter *must* be specified (see Example 6-8).

Example 6-8 JCL for SMF records extraction, preserving SMF digital signature

```
//IFASMF DL EXEC PGM=IFASMF,REGION=0M
//OUTDD1 DD DSN=REDBOOK.SMF.LOGS,DISP=(NEW,CATLG,DELETE),
//        SPACE=(CYL,(100,100),RLSE),
//        DCB=(LRECL=32760,RECFM=VBS,BLKSIZE=0)
//SYSPRINT DD SYSOUT=A
//SYSIN DD *
LSNAME(IFASMF.ALLSYS.DATA,OPTIONS(DUMP))
OUTDD(OUTDD1,TYPE(0:255),START(1400),END(2000))
NOSIGSTRIP
DATE(2022096,2022096)
```

Step 4: Validating the SMF signature

By using the IFASMFDP utility, we can specify the SIGVALIDATE parameter along with the hashing method and the name of the token. The utility validates the records and ensures that they are all signed with the specified token (see Example 6-9).

Tip: You do not have to write out records to another data set when performing validation, as we show in the example. An alternative is to use a [dummy data set](#), by replacing the DDSMF1 DD statements with DDSMF1 DD DUMMY.

Example 6-9 JCL to create SMF records signing validation

```
//SMF      EXEC      PGM=IFASMFDP
//DUMPIN   DD  DISP=SHR,DSN=RBOOK.SMF.LOGS
//DDSMF1   DD  DSN=RBOOK.SMF.RACF,
//          DISP=(NEW,CATLG,DELETE),
//          SPACE=(CYL,(100,100),RLSE),
//          DCB=(RECFM=VBS,BLKSIZE=32748,LRECL=32756)
//SYSPRINT DD  SYSOUT=A
//SYSIN    DD  *
SID(SYSA)
INDD(DUMPIN,OPTIONS(DUMP))
OUTDD(DDSMF1,TYPE(30,82))
NOSIGSTRIP
DATE(2022096,2022096)
START(1400) END(1800)
SIGVALIDATE(HASH(SHA512),
            TOKENNAME(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS1))
```

Sample output from the SMF records signing validation job is shown in Example 6-10.

Example 6-10 SMF records signing validation report

```
IFA010I SMF DUMP PARAMETERS
IFA010I REPORTOPTS(NOSUBTYPE) -- DEFAULT
IFA010I NOASIGVALIDATE -- DEFAULT
IFA010I SIGVALIDATE(HASH(SHA512),
            TOKENNAME(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS1)) -- SYSIN
```

```
IFA010I END(1800) -- SYSIN
IFA010I START(1400) -- SYSIN
IFA010I DATE(2022096,2022096) -- SYSIN
IFA010I NOSIGSTRIP -- SYSIN
IFA010I OUTDD(DDSMF1,TYPE(30,82)) -- SYSIN
IFA010I INDD(DUMPIN,OPTIONS(DUMP)) -- SYSIN
IFA010I SID(SYSA) -- SYSIN
IFA020I DDSMF1 -- RBOOK.SMF.RACF
IFA020I DUMPIN -- RBOOK.SMF.LOGS
```

SUMMARY ACTIVITY REPORT

START DATE-TIME 04/06/2022-14:00:00			END DATE-TIME 04/06/2022-19:59:58			
RECORD	RECORDS	PERCENT	AVG. RECORD	MIN. RECORD	MAX. RECORD	RECORDS
TYPE	READ	OF TOTAL	LENGTH	LENGTH	LENGTH	WRITTEN
2	5,974	4.35 %	347.85	18	356	447
3	1	.00 %	18.00	18	18	1
23	24	.02 %	8,062.00	8,062	8,062	0
30	20,995	15.29 %	1,529.65	480	6,121	3,244

42	5,674	4.13 %	2,473.64	176	32,444	0
70	1,224	.89 %	20,887.45	1,672	32,600	0
71	288	.21 %	2,596.00	2,596	2,596	0
72	13,824	10.06 %	1,791.39	1,324	13,328	0
73	288	.21 %	29,216.00	29,216	29,216	0
74	5,616	4.09 %	10,474.92	308	32,520	0
75	576	.42 %	272.00	272	272	0
77	288	.21 %	585.25	328	832	0
78	576	.42 %	6,428.00	4,056	9,008	0
82	47	.03 %	120.00	120	120	31
99	75,619	55.06 %	2,877.35	419	8,870	0
113	6,336	4.61 %	1,606.00	1,462	1,834	0
TOTAL	137,350	100 %	2,901.58	18	32,600	3,723
NUMBER OF RECORDS IN ERROR			0			

RECORD VALIDATION REPORT FOR SYSA							
RECORD TYPE	RECORD SUBTYPE	VALIDATION FAILURE	VALIDATION START DATE-TIME	VALIDATION END DATE-TIME	RECORDS VALIDATED	GROUPS VALIDATED	INTERVALS VALIDATED
30	2	N	04/06/2022-14:00:00	04/06/2022-18:00:00	2,620	73	48
30	6	N	04/06/2022-14:00:00	04/06/2022-18:00:00	624	48	48
30	3	N	04/06/2022-14:00:00	04/06/2022-18:00:00	0	0	48
30	4	N	04/06/2022-14:00:00	04/06/2022-18:00:00	0	0	48
30	5	N	04/06/2022-14:00:00	04/06/2022-18:00:00	0	0	48
82	20	N	04/06/2022-14:00:00	04/06/2022-18:00:00	31	31	48
VALIDATION SUCCEEDED							

Implementing SMF alternative signatures

As described in “Impact of Shor’s and Grover’s algorithms” on page 7, traditional public key cryptography, such as RSA and ECC, can be compromised by a quantum computer that is running Shor’s algorithm. To maintain a safe way to validate SMF audit data, you can use a function that was introduced with z/OS 2.4 that allows a secondary (or alternative) signature that uses CRYSTALS-Dilithium.

Step 1: Generate the PKCS #11 CRYSTALS-Dilithium key pair

Note: As of this writing, SMF alternative signature support is for CRYSTALS-Dilithium 65 Round 2 only.

The PKCS #11 CRYSTALS-Dilithium key pair can be clear or secure. For a secure key pair, an Enterprise PKCS #11 coprocessor Crypto Express7S or later must be available with the suitable ICSF minimum service level. The minimum hardware and software levels are listed in Table 4-2 on page 55.

For more information about generating PKCS #11 CRYSTALS-Dilithium key pair services, see 6.4.4, “Generating CRYSTALS-Dilithium key by using ICSF PKCS #11 services” on page 104.

Step 2: Configuring SMF for alternative digital signature

Example 6-11 shows an SMFPRMxx parmlib member (truncated) that enables an SMF digital signature, and alternative digital signature for a log stream that stores z/OS events. The alternative signature is specified in SMFPRMxx by using the ARECSIGN parameter and the RECSIGN parameter. When ARECSIGN is used, RECSIGN also must be specified. The specified TOKENNAME must be the PKCS #11 token that contains the CRYSTALS-Dilithium key object.

Example 6-11 SMFPRMxx parmlib member that enables SMF digital signature for SMF log streams

```
ACTIVE                                /*ACTIVE SMF RECORDING*/
```

```

LISTDSN                /* LIST DATA SET STATUS AT IPL*/
NOPROMPT                /*DON'T PROMPT THE OPERATOR */
DEFAULTLSNAME(IFASMF.ALLSYS.DEFAULT,COMPRESS(PERMFIX(32M)))
LSNAME(IFASMF.ALLSYS.DATA,TYPE(0,23,30,42,70:79,80:83,99,113),
      COMPRESS(PERMFIX(64M))
      RECSIGN(HASH(SHA512),SIGNATURE(RSA),
      TOKENNAME(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS1))
      ARECSIGN(HASH(SHA512),SIGNATURE(LI2),
      TOKENNAME(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS2))
)
RECORDING(LOGSTREAM)

```

Step 3: Extracting the data from the log stream

Although the extraction process did not change, we still need to use the NOSIGSTRIP parameter to preserve the record signatures (see Example 6-12).

Example 6-12 JCL for SMF records extraction, preserving SMF digital signature

```

//IFASMF DL EXEC PGM=IFASMF DL,REGION=0M
//OUTDD1 DD DSN=RBOOK.SMF.LOGS,DISP=(NEW,CATLG,DELETE),
//        SPACE=(CYL,(100,100),RLSE),
//        DCB=(LRECL=32760,RECFM=VBS,BLKSIZE=0)
//SYSPRINT DD SYSOUT=A
//SYSIN DD *
LSNAME(IFASMF.ALLSYS.DATA,OPTIONS(DUMP))
OUTDD(OUTDD1,TYPE(0:255),START(1400),END(2000))
NOSIGSTRIP
DATE(2022096,2022096)

```

Step 4: Validating the SMF signature

Here, we want to specify the SIGVALIDATE *and* ASIGVALIDATE parameters (see Example 6-13).

Example 6-13 JCL to create SMF records signing validation including alternative signature

```

//SMF EXEC PGM=IFASMF DP
//DUMPIN DD DISP=SHR,DSN=RBOOK.SMF.LOGS
//DDSMF1 DD DSN=RBOOK.SMF.RACF,
//        DISP=(NEW,CATLG,DELETE),
//        SPACE=(CYL,(100,100),RLSE),
//        DCB=(RECFM=VBS,BLKSIZE=32748,LRECL=32756)
//SYSPRINT DD SYSOUT=A
//SYSIN DD *
SID(SYSA)
INDD(DUMPIN,OPTIONS(DUMP))
OUTDD(DDSMF1,TYPE(30,82))
NOSIGSTRIP
DATE(2022096,2022096)
START(1400) END(1800)
SIGVALIDATE(HASH(SHA512),
      TOKENNAME(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS1))
ASIGVALIDATE(HASH(SHA512),
      TOKENNAME(QSAFE.REDBOOK.SMF.SIGN.TOKEN.LS2))

```

6.7 Quantum-safe hybrid key exchange

Key exchange allows two parties to establish a shared secret by using public key cryptography.

With the introduction of the CRYSTALS-Kyber algorithm, is it now possible to perform a quantum-safe hybrid key exchange scheme that combines the protection of traditional Elliptic Curve Cryptography (ECC) and the quantum-safe CRYSTALS-Kyber algorithm. This hybrid key exchange scheme provides two layers of protection and ensures that all key exchanges are protected from attacks by traditional and quantum computers.

For more information about how organizations can use secure key exchange to protect their sensitive data, see 3.2, “Use case: Sharing keys securely” on page 31.

This section describes how to perform a quantum-safe hybrid key exchange by using CCA and PKCS #11 services.

6.7.1 Performing a hybrid quantum-safe key exchange scheme by using ICSF CCA services

A hybrid quantum-safe key exchange can be performed with the PKA Encrypt (CSNDPKE and CSNFPKE) and EC Diffie-Hellman (CSNDEDH and CSNFEDH) ICSF services.

The following Access Control Points (ACP) must be enabled:

- ▶ PKA Encrypt -Allow CRYSTALS-Kyber keys (0083x)
- ▶ EC Diffie-Hellman -Allow Hybrid QSA Scheme (035Dx)

Consider the following hybrid quantum-safe key exchange scheme that includes two participants: Alice and Bob are two parties who want securely exchange information. They can be a company and a Business Partner, for example.

Step 1: Alice

1. Alice creates the following keys:
 - Kyber-priv-A, Kyber-pub-A: CRYSTALS-Kyber 1024 key pair
 - EC-priv-A, EC-pub-A: ECC key pair for key agreement
 - Kyber-cert-A, EC-cert-A: authentication forms of Kyber-pub-A and EC-pub-A
2. Alice sends Kyber-cert-A and EC-cert-A to Bob.

Step 2: Bob

1. Bob receives and validates Kyber-cert-A and EC-cert-A
2. Bob creates the following keys:
 - AES-ciph-B: AES CIPHER key in a CCA key token

Note: AES-ciph-B must be as strong as the derived shared key (for example, AES 256-bit) and allow encrypt *and* decrypt operations.

- EC-priv-B, EC-pub-B: ECC key pair for key agreement
- EC-cert-B: authenticated form of EC-pub-B
- Kyber-pub-A CCA public key token with public key pulled from Kyber-cert-A

3. Bob creates the shared key derivation input by using the CSNDPKE service:
 - RANDOM keyword, AES-ciph-B, Kyber-pub-A, AES encryption IV
 - Generates a random 32B value: rand-32
 - AES-CBC encrypts rand-32 by using key AES-ciph-B and the AES encryption IV returning [AES-ciph-B(rand-32)] in the keyvalue parameter.
 - CRYSTALS-Kyber encrypts rand-32 with Kyber-pub-A returning [Kyber-pub-A(rand-32)] in the PKA_enciphered_keyvalue parameter.
4. Bob completes the shared key derivation by using CSNDEDH

Bob calls CSNDEDH by using a derivation keyword and wanted key length, [AES-ciph-B(rand-32)], AES-ciph-B, AES encryption IV, EC-priv-B, EC-cert-A, output skeleton token.

Consider the following points about CSNDEDH:

 - Decrypts rand-32 by using the key AES-ciph-B and the AES encryption IV.
 - Uses EC-priv-B and EC-cert-A with ECDH to generate the Z value.
 - Passes Z and rand-32 to the key derivation function that is indicated by the derivation keyword, rand-32 is the salt or OtherData. The shared key of the requested length is derived.
 - Places the shared key in the provided output skeleton token and then, encrypts the key value.
 - Returns the final CCA shared key token.
5. Bob stores the shared key
6. Bob sends EC-cert-B, [Kyber-pub-A(rand-32)] to Alice.

Step 3: Alice

1. Alice receives and validates EC-cert-B, [Kyber-pub-A(rand-32)].
2. Alice completes the shared key derivation by using CSNDEDH

Alice calls CSNDEDH with a derivation keyword and the wanted key length, [Kyber-pub-A(rand-32)], Kyber-priv-A, EC-priv-A, EC-cert-B, output skeleton token.

Consider the following points about CSNDEDH:

 - Decrypts rand-32 by using Kyber-priv-A.
 - Uses EC-priv-A and EC-cert-B with ECDH to generate the Z value.
 - Passes Z and rand-32 to the key derivation function that is indicated by the derivation keyword, rand-32 is the salt or OtherData. The shared key of the requested length is derived.
 - Places the shared key in the provided output skeleton token and then, encrypts the key value.
 - Returns the final CCA shared key token.
3. Alice stores the shared key.

The shared key is now established by Alice and Bob.

Role of CSNDPKE

The role of the PKA Encrypt (CSNDPKE) service in this scheme is to create the rand-32 derivation input and return rand-32 in the following forms:

- ▶ Encrypted by Bob's AES cipher key, AES-ciph-B
- ▶ Encrypted by Alice's CRYSTALS-Kyber public key, Kyber-pub-A

This process is accomplished in one call to CSNDPKE:

- ▶ Inputs:
 - RANDOM rule-array keyword
 - AES-ciph-B: AES-cipher key for Bob

Note: AES-ciph-B must be as strong as the derived shared key.

- Kyber-pub-A as PKA_key_identifier: CRYSTALS-Kyber key for Alice
- ▶ Outputs:
 - keyvalue parameter: [AES-ciph-B(rand-32)]
 - PKA_enciphered_keyvalue parameter: [Kyber-pub-A(rand-32)]

Consider the following points:

- ▶ Authentication of the public keys that are used in the scheme is the responsibility of the host.

Currently, CRYSTALS-Kyber keys do not participate in PKI processes. The kyber-cert-A certificate for a CRYSTALS-Kyber public key recognizes that certificate formats are needed for the authentication part of a protocol.

For the ECC public keys, the CCA internal PKI can be used for authentication if the trust anchor was installed in the adapter.
- ▶ A full protocol must include a Key Check Value that is calculated over the shared key that was created by Bob so that Alice can verify the creation of an agreed shared key.

For more information about a REXX sample that shows this end-to-end scheme that uses ICSF CCA services, see E.1, "CCA hybrid quantum-safe key exchange scheme REXX sample" on page 166.

For more information about these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.7.2 Performing a hybrid quantum-safe key exchange scheme by using ICSF PKCS #11 services

A hybrid quantum-safe key exchange can be performed by using the PKCS #11 Derive Key (CSFPDVK and CSFPDVK6) ICSF service.

Consider the following hybrid quantum-safe key exchange scheme that includes two participants: Alice and Bob, who are two parties that want to securely exchange information. They can be a company and a Business Partner, for example.

Step 1: Alice

1. Alice generates an ECC key pair (EC-pub-A, EC-priv-A) for key agreement by using the PKCS #11 Generate Key Pair service.
2. Alice creates EC-cert-A: authenticated form of EC-pub-A

3. Alice sends EC-cert-A to Bob.

Step 2: Bob

1. Bob receives and validates EC-cert-A.
2. Bob creates the following keys:
 - ECC (EC-pub-B, EC-priv-B) key pair for key agreement by using the PKCS #11 Generate Key Pair service.
 - CRYSTALS-Kyber (Kyb-pub-B, Kyb-priv-B) key pair by using the PKCS #11 Generate Key Pair service.
 - EC-pub-A PKCS #11 public key object that was pulled from EC-cert-A by using the PKCS #11 Token Record Create service.
 - Kyb-cert-B and EC-cert-B: authenticated forms of Kyb-pub-B and EC-pub-B.
3. Bob derives a generic secret key object (GenSec-B) by passing EC-priv-B *and* EC-pub-A to PKCS #11 Derive Key.
4. Bob sends Kyb-cert-B and EC-cert-B to Alice.

Step 3: Alice

1. Alice receives and validates Kyb-cert-B and EC-cert-B.
2. Alice creates Kyb-pub-B and EC-pub-B PKCS #11 public key objects that were pulled from their respective certificates by using the PKCS #11 Token Record Create service.
3. Alice derives a generic secret key object (GenSec-A) by passing EC-priv-A *and* EC-pub-B to PKCS #11 Derive Key.
4. Alice passes GenSec-A and Kyb-pub-B to PKCS #11 Derive Key to encapsulate random key material (rand-A). The Kyber-encapsulated random key material [Kyb-pub-B(rand-A)] and derived shared key are returned. The shared key is the output in the target_key_handle parameter.
5. Alice sends to Bob the Kyber-encapsulated random key material [Kyb-pub-B(rand-A)].

Step 4: Bob

Bob passes GenSec-B and Kyb-priv-A to PKCS #11 Derive Key to decapsulate [Kyb-pub-B(rand-A)]. The derived shared key is output in the target_key_handle parameter.

The shared key is now established at Alice and Bob.

Authentication of the public keys that are used in the scheme is the responsibility of the host.

Currently, CRYSTALS-Kyber keys do not participate in PKI processes. The Kyb-cert-B certificate for the CRYSTALS-Kyber public key recognizes that certificate formats are needed for the authentication part of a protocol.

The lack of PKI support for CRYSTALS-Kyber can be circumvented by using a trustworthy public RSA or EC certificate to verify a signed Kyber SPKI.

For more information about a REXX sample that shows this end-to-end scheme that uses ICSF PKCS #11 services, see E.2, “PKCS #11 hybrid quantum-safe key exchange scheme REXX sample” on page 176.

For more information about these services and parameters, see the *ICSF Application Programmer's Guide*, SC14-7508.

6.8 Quantum-safe hashing

Hashing is the process of transforming data (for example a key or message) into a shorter, fixed-length message digest by using a cryptographic hash algorithm.

Hashes are used in various cryptographic operations, such as digital signatures, and key derivation functions, such as PBKDF2, Message Authentication Codes (MAC). The message digests that are produced from a hash algorithm ensures the integrity of the data and protects against unauthorized alteration of the source data.

It is important to start transitioning from weaker hash algorithms, such as SHA-1 or MD2, to much stronger hash algorithms, such as SHA-256 or SHA-512.

This section describes how to perform an SHA-512 hash over a message by using CCA and PKCS #11 ICSF services.

6.8.1 Hashing a message with the SHA-512 algorithm by using ICSF CCA services

To hash a message by using the SHA-512 algorithm, use the One-Way Hash Generate (CSNBOWH or CSNBOWH1 and CSNEOWH or CSNEOWH1) ICSF service.

To hash a message by using the SHA-512 algorithm, complete the following steps:

1. Call the CSFBOWH ICSF service that passes the SHA-512 and ONLY rules.
2. Pass the message to hashed in the text parameter. (Optionally, the message can be hashed in parts by using the chaining flag rules and the chaining_vector parameter.)

The 64-byte message digest is output in the hash parameter.

For more information about a sample REXX program that showcases this process, see F.1, “CCA SHA-512 one-way hash REXX sample” on page 188.

For more information about this service and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.8.2 Hashing a message with the SHA-512 algorithm by using ICSF PKCS #11 services

To hash a message by using the SHA-512 algorithm, use the PKCS #11 One-Way Hash, Sign, or Verify (CSFPOWH and CSFPOWH6) ICSF service.

To hash a message by using the SHA-512 algorithm, complete the following steps:

1. Initialize a PKCS #11 token by using the PKCS #11 Token Record Create (CSFPTRC and CSFPTRC6) service.
2. Call the CSFPOWH ICSF service that passes the SHA-512 and ONLY rules.
3. Pass the message to hashed in the text parameter.
4. Pass the token handle that was created in step one in handle parameter. (Optionally, the message can be hashed in parts by using the chaining flag rules and the chaining_vector parameter.)

The 64-byte message digest is output in the hash parameter.

For more information about a sample REXX program that showcases step 2, see F.2, “PKCS #11 SHA-512 one-way hash REXX sample” on page 189.

For more information about these services and parameters, see *ICSF Application Programmer's Guide*, SC14-7508.

6.9 Validating your quantum-safe transition

As discussed in 5.1, “Collection tools overview” on page 72, the usage statistics are key to a comprehensive cryptographic inventory.

In Example 6-14, we can see that non-quantum-safe algorithms are used in our DATAOWN job (which is a formatted report of SMF record type 82, subtype 31 [hex '001F']). We can identify the use of single DES, AES 128, weak RSA 1024, and so on.

Example 6-14 Crypto usage statistics: Checking for non-quantum-safe algorithms

```
Type=82 Subtype=001F Crypto Usage Statistics
Written periodically to record crypto usage counts
22 Feb 2022 15:12:27.73
TME... 005389D5 DTE... 0122053F SID... SP21    SSI... 00000000 STY... 001F
INTVAL_START.. 02/22/2022 19:11:30.001815
INTVAL_END.... 02/22/2022 19:12:27.737573
USERID_AS.....DATAOWN
USERID_TK.....
JOBID.....J0000055
JOBNAME.....DATAOWN
JOBNAME2.....
PLEXNAME.....SYS1
DOMAIN.....0
ENG...CARD...8C11/99EA6127...17
ENG...CPACF...150
ALG...DES56.....2
ALG...AES128.....2
ALG...RSA1024....1
ALG...ECCBP192...1
ALG...MD5.....45
ALG...RPM160....15
ALG...SHA1..... 70
ALG...SHA3-224... 13
ALG...SHA3-256... 15
ALG...SHA3-384... 13
ALG...SHA3-512... 13
ALG...SHAKE128... 12
ALG...SHAKE256... 14
SRV...CSFKYT..... 2
SRV...CSFDSG..... 2
SRV...CSFOWH..... 264
SRV...CSFOWH1.... 3
SRV...CSFIQF..... 485
SRV...CSFIQF2.... 2
```

After identifying the weak algorithms and replacing them with quantum-safe algorithms, ICSF usage statistics can be used to monitor progress with a formatted report of SMF record type 82, subtype 31 (hex '001F').

In Example 6-15, most algorithms are quantum-safe. For example, we no longer use AES 128; instead, we use AES 256. We can also see that CRYSTALS-Dilithium and CRYSTALS-Kyber algorithms are being used.

Example 6-15 Crypto usage statistics: Checking for quantum-safe algorithms

```
Type=82 Subtype=001F Crypto Usage Statistics
Written periodically to record crypto usage counts
Mar 2022 15:35:30.00
TME... 0055A5C8 DTE... 0122070F SID... SP21      SSI... 00000000 STY... 001F
INTVAL_START.. 03/11/2022 19:33:59.202360
INTVAL_END.... 03/11/2022 19:35:30.001479
USERID_AS..... QSAFE
USERID_TK.....
JOBID..... T0000046
JOBNAME..... QSAFE
JOBNAME2.....
PLEXNAME..... SYS1
DOMAIN..... 0
ENG...CARD...8C00/99EA6006... 17
ENG...CPACF... 5
ALG...DES112..... 1
ALG...AES256..... 9
ALG...ECCP384.... 6
ALG...KY1024R2... 3
ALG...LI2-87R3... 4
SRV...CSFDSG..... 2
SRV...CSFDSV..... 2
SRV...CSFPKG..... 3
SRV...CSFPKE..... 1
SRV...CSFPKX..... 3
SRV...CSFKYT2.... 2
SRV...CSFEDH..... 2
SRV...CSFPKB..... 3
SRV...CSFCTT2.... 1
```

Important: Data that is protected with a retired algorithm must not remain in the system after it is protected by using a quantum-safe algorithm. Removing the data that was encrypted by using a retired algorithm eliminate the risk of an attacker finding that data and breaking the encryption.



A

Finding cryptographic attributes

The purpose of this appendix is to introduce a process that can be used when creating your cryptographic inventory with the available tools. The output from this process helps you to make qualified choices in terms of protecting your programs and applications against future threats from quantum computer attacks, which are also known as a *cryptographically relevant quantum computer* (CRQC) attacks.

The suggested process requires manual analysis to discover which cryptographic algorithms, key lengths, and key labels are used in your programs and applications.

For more information, see “Establishing a cryptographic inventory” on page 58 and Chapter 5, “Creating a cryptographic inventory” on page 71.

This appendix includes the following topics:

- ▶ A.1, “Tools for cryptographic inventory” on page 122
- ▶ A.2, “Investigation process” on page 123
- ▶ A.3, “Process that was used” on page 125

A.1 Tools for cryptographic inventory

The examples that are used in this appendix show how cryptographic attributes can be located for a COBOL program by using the following IBM Z tools:

- ▶ **System Display and Search Facility (SDSF) Job Listing**

This utility allows you to monitor, control, and view the output of jobs in the system. After submitting a job, it is common to use SDSF to review the output for successful completion, or to review and correct JCL errors.

- ▶ **ICSF System Management Facility (SMF) records:**

ICSF uses SMF record type 82 to record certain ICSF events. The following recorded information is important to our discussion:

- Sub-type 31, which contains cryptographic statistics data for cryptographic engines (ENG), cryptographic services (SRV), and cryptographic algorithms (ALG) for a Logical Partition (LPAR)
- Sub-types 40 – 42, which contains ICSF key lifecycle events.
- Sub-types 44 – 46, which contains ICSF key usage events.

- ▶ **IBM Application Discovery and Delivery Intelligence**, which provides API call information from scanning COBOL applications.

- ▶ **IBM Crypto Analytics Tool (CAT)**, which provides information about the cryptographic entities, including the key material and key data sets.

For more information about tools, see Chapter 5, “Creating a cryptographic inventory” on page 71.

A.2 Investigation process

You can start the investigation process based on output from any of the four IBM tools, as shown in Figure A-1.

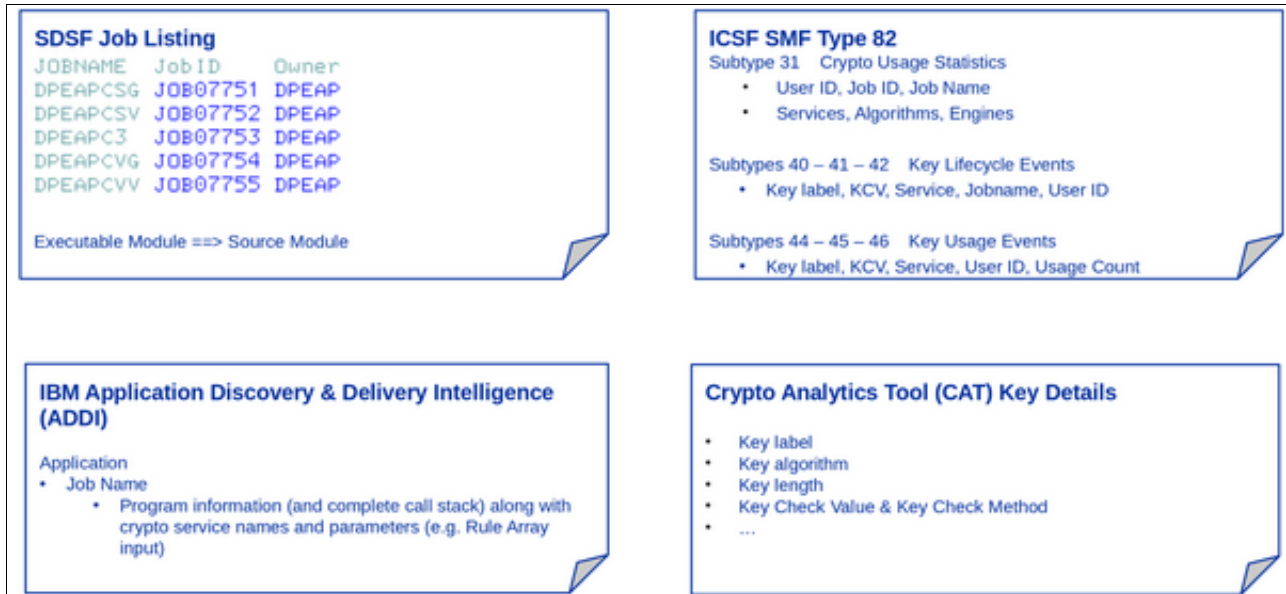


Figure A-1 Tools for cryptographic inventory

The investigation process and steps vary depending on the output from the tool with which you start. The different steps are described next.

A.2.1 Starting with application source code scan from IBM ADDI

If you are starting with application source code that was scanned by IBM ADDI and uses cryptography, complete the following steps:

1. Select the application source code from the ADDI scan that you want to investigate.
2. Identify the ProgramName in the ADDI scan of the application source code.
3. Determine the job or started task that runs the executable.
4. Create reports from ICSF SMF record type 82:
 - Tailor CSFSMFJ in SYS1.SAMPLIB to fit your environment.
 - Run CSFSMFJ.
5. Identify the ICSF services that are called by the job or started task and the related key material from the SMF records.
6. Review the key details from the CAT snapshot.

A.2.2 Starting with a policy check in the IBM CAT

If you ran a policy check in the IBM CAT component and now have a list of keys from your keystores that are deemed to be weak keys, complete the following steps:

1. Review the key details from the CAT policy scan in the snapshot.
2. Create reports from ICSF SMF record type 82 that reference the key details by key label or by key check value (KCV):
 - Tailor CSFSMFJ in SYS1.SAMPLIB to fit your environment
 - Run CSFSMFJ
3. Identify the ICSF service calls that relate to the key material from the SMF records.
4. Determine the job or started task from the ICSF SMF records.
5. Identify the executable from the job listing in SDSF and application source code.
6. Review the ADDI scanning of the application source code.

A.2.3 Starting with an application that you know

If you know the application that uses cryptographic functions, complete the following steps:

1. Select the application jobs or started tasks in the SDSF job listing.
2. Determine the application source code from the executable from the job.
3. Create reports from ICSF SMF record type 82:
 - Tailor CSFSMFJ in SYS1.SAMPLIB to fit your environment
 - Run CSFSMFJ
4. Identify the ICSF service calls that relate to key material from the ICSF SMF records.
5. Verify the ADDI scanning of the application source code.
6. Review the key details from the CAT snapshot.

A.2.4 Starting with SMF record type 82 reports

If you find SMF 82 subtype 31 records that indicate the use of weak cryptographic algorithms, complete the following steps:

1. Identify the jobs or started tasks and users, ICSF service calls, and key material from the SMF 82 records.
2. Find the jobs or started tasks from the SMF records in the SDSF job listing.
3. Identify the executable modules from the SDSF job listing.
4. Determine the application source code from the executable.
5. Verify the ADDI scanning of the application source code.
6. Review the key details from the CAT snapshot.

Regardless of the investigation process that you decide to use, all findings of the cryptographic usage and configuration in your environment must be documented in your cryptographic inventory, as described in “Establishing a cryptographic inventory” on page 58.

A.3 Process that was used

In this section, we provide examples of how to proceed with the investigation process by using an ADDI scanning of a set of source modules, as described in A.2.1, “Starting with application source code scan from IBM ADDI” on page 123. Examples of key usage events and a key lifecycle event are provided.

A.3.1 Examples of finding key usage events

In Figure A-2, we can see that a source module and a few sub modules were ADDI scanned. The program is called DKMSKSA (see the ProgramName column).

OccurID	APIName	APIDescription	APIID	OrParamValue	GroupID	Descripti	VarName	ProgramName	StartRow
10289	CSNBENC	Encipher	DES	9	3	1 CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	8960
10289	CSNBENC	Encipher	DES	10 CBC INITIAL DES	1	CRYPTO	CSFSERV-RULE-A	DKMSKSA	8960
10396	CSNBENC	Encipher	DES	9	3	1 CRYPTO	CSFSERV-RULE-A-COUNT	DKMSKSA	9202
10396	CSNBENC	Encipher	DES	10 CBC INITIAL DES	1	CRYPTO	CSFSERV-RULE-A	DKMSKSA	9202

Figure A-2 Sample1: Source module

Next, we identify two cryptographic functions that are used by DKMSKSA and map them to the key material.

A call to APIName CSNBENC that is found in DKMSKSA shows the StartRow (8960 and 9202) of the call to CSNBENC.

The value that is shown in the StartRow column is the line number in DKMSKSA where CSNBENC is called.

To map the APIName from CCA to an ICSF service call from the ProgramName and APIDescription, we must take a short detour. In Figure A-3, we can see that the ICSF entry point name (CSFENC) corresponds to the CCA entry point name (CSNBENC).

Descriptive service name	CCA entry point names		ICSF entry point names		SAF resource name	Callable service exit name
	31-bit	64-bit	31-bit	64-bit		
Encipher	CSNBENC	CSNEENC	CSFENC	CSFENC6	CSFENC	CSFENC

Figure A-3 Resource names for CCA and ICSF entry points: Encipher

The CCA and ICSF entry point names tell you which cryptographic operations are being used.

The DKMSRKX source module also does a call to CSNDRKX (see Figure A-4). It can be seen that the CSNDRKX call is made from StartRow 395 in DKMSRKX (ProgramName).

OccurID	APIName	APIDescription	APIID	OrParamValue	GroupID	Descripti	VarName	ProgramName	StartRow
2518	CSNDRKX	Remote Key Export	DES	5	1	1 CRYPTO	C-RULE-ARRAY-COUNT	DKMSRKX	395
2518	CSNDRKX	Remote Key Export	DES	6		1 CRYPTO	C-RULE-ARRAY	DKMSRKX	395

Figure A-4 Sample 2: Source module

Once again to map the APIName from CCA to an ICSF service call from the ProgramName and APIDescription, we must take a short detour. In Figure A-5 we can see that the ICSF entry point name (CSNDRKX) corresponds to the CCA entry point name (CSFRKX).

Descriptive service name	CCA entry point names		ICSF entry point names		SAF resource name	Callable service exit name
	31-bit	64-bit	31-bit	64-bit		
Remote Key Export	CSNDRKX	CSNFRKX	CSFRKX	CSFRKX6	CSFRKX	CSFRKX

Figure A-5 Resource names for CCA and ICSF entry points - Remote Key Export

For more information about resource names for CCA and ICSF entry points, see CCA and ICSF entry points, see *ICSF Application Programmer's Guide*, [SC14-7508](#).

Having identified the two ICSF service calls, we now proceed to the next step in the investigation process: identifying the executable module from the source module. This process requires that you understand the steps that are involved in building an executable from application source code and finding the name of the executable.

In our environment, we determined that the DKMSKSA includes the DKMSRKX source code.

Next, we identify the corresponding job execution from the SDSF job listing. At this point, application knowledge is needed in terms of which jobs are involved in executing DKMSKSA and how the program invocation is made. Figure A-6 shows a list of the jobs that execute the DKMSKSA program. The jobs executed on 25 May 2022 (05/25/2022) around 7:00 AM.

File Options									
Display Filter View Print Options Search Help									
SDSF	HELD	OUTPUT	DISPLAY	ALL	CLASSES	LINES	530,551	LINE 24-59 (106)	
NP	JOBNAME	JobID	Owner	Priy	C	ODisp	Dest	Tot-Rec	Tot-
	DPEAPCSG	JOB07751	DPEAP	144	T	HOLD	LOCAL	194	
	DPEAPCSV	JOB07752	DPEAP	144	T	HOLD	LOCAL	198	
	DPEAPC3	JOB07753	DPEAP	128	T	HOLD	LOCAL	327	
	DPEAPCVG	JOB07754	DPEAP	128	T	HOLD	LOCAL	213	
	DPEAPCVV	JOB07755	DPEAP	128	T	HOLD	LOCAL	222	
	DPEAPDER	JOB07756	DPEAP	96	T	HOLD	LOCAL	1,039	
	DPEAPGT	JOB07757	DPEAP	128	T	HOLD	LOCAL	223	
	DPEAPG	JOB07759	DPEAP	144	T	HOLD	LOCAL	194	
	DPEAPPD	JOB07760	DPEAP	128	T	HOLD	LOCAL	258	
	DPEAPPE	JOB07761	DPEAP	128	T	HOLD	LOCAL	481	
	DPEAPCL	JOB07762	DPEAP	144	T	HOLD	LOCAL	189	
	DPEAPPD	JOB07763	DPEAP	144	T	HOLD	LOCAL	187	
	DPEAPPG	JOB07764	DPEAP	128	T	HOLD	LOCAL	239	
	DPEAPPD	JOB07765	DPEAP	128	T	HOLD	LOCAL	228	
	DPEAPRM	JOB07766	DPEAP	128	T	HOLD	LOCAL	229	
	DPEAPPV	JOB07767	DPEAP	128	T	HOLD	LOCAL	254	
	DPEAPXL	JOB07768	DPEAP	128	T	HOLD	LOCAL	231	
	DPEAPOF	JOB07773	DPEAP	128	T	HOLD	LOCAL	238	
	DPEAPRM1	JOB07774	DPEAP	112	T	HOLD	LOCAL	812	
	DPEAPSDA	JOB07775	DPEAP	128	T	HOLD	LOCAL	256	
	DPEAPTCV	JOB07776	DPEAP	128	T	HOLD	LOCAL	252	

Figure A-6 Job listing

Important: The job execution time is needed to identify the relevant SMF records.

For our example, we identified the job IDs that are based on the DKMSKSA program in the JCL libraries. This task also is manual.

Using two jobs as examples for SMF record type 82 subtypes 31 and 44 correlation, we look at job IDs JOB07760 and JOB07761 from Figure A-6 on page 126.

By looking at the JCL library for the two members for DPEAPPD (JOB07760) and DPEADPE (JOB07761), we can determine from the SYSTSIN statement which program is to be run.

In Example A-1, we see job DPEAPPD runs program PANDEC.

Example A-1 JCL for DPEAPPD

```
//DPEAPPD JOB (9060-02292-01-33,LU2),'RUN PANDEC ',
//          MSGCLASS=T,CLASS=G,MSGLEVEL=(1,1)
/*JOBPARM S=MVSF
/*-----
//RUNAPI   EXEC   PGM=IKJEFT01,REGION=OM
//STEPLIB  DD  DISP=SHR,DSN=DPLMF.KSA0501X.LOAD
//          DD  DISP=SHR,DSN=DPLMF.KSA0501X.LOADD
//          DD  DSN=DB2FSYS.SDSNEXIT,DISP=SHR
//          DD  DSN=DB2FSYS.SDSNLOAD,DISP=SHR
//SYSTSIN  DD  *
DSN SYST(DB2F)
RUN PROGRAM(PANDEC) PLAN(KSA0501V)
END
```

In Example A-2, we see job DPEAPPE runs program PANENC.

Example A-2 JCL for DPEAPPE

```
//DPEAPPE JOB (9060-02292-01-33,LU2),'RUN PANENC ',
//          MSGCLASS=T,CLASS=G,MSGLEVEL=(1,1)
/*JOBPARM S=MVSF
/*ABCDE-----
//RUNAPI   EXEC   PGM=IKJEFT01,REGION=OM
//STEPLIB  DD  DISP=SHR,DSN=DPLMF.KSA0501X.LOAD
//          DD  DISP=SHR,DSN=DPLMF.KSA0501X.LOADD
//          DD  DSN=DB2FSYS.SDSNEXIT,DISP=SHR
//          DD  DSN=DB2FSYS.SDSNLOAD,DISP=SHR
//SYSTSIN  DD  *
DSN SYST(DB2F)
RUN PROGRAM(PANENC) PLAN(KSA0501V)
END
```

Both programs (PANDEC and PANENC) call the DKMSKSA program. Although the input parameters are different, this issue is irrelevant in the context of mapping the key material and ICSF services to DKMSKSA.

In Example A-3, we can see PANENC calls DKMSKSA.

Example A-3 PANENC calls DKMSKSA

```
BA-CALL-DKMSKSA SECTION.
*****
* CALL DKMSKSA
*****
```

```
CALL DKMSKSA USING DAPI-KSA-V01
DISPLAY 'API RETURN-CODE = ' RETURN-CODE
```

We have two job IDs (JOB07760 and JOB07761) that run program DKMSKSA. Now, we need to identify the ICSF SMF record type 82 entries. We want to search for subtypes 31, 40 – 42, and 44 – 46 in the timeframe in which the job was run. In our environment, SMF records are collected in half-hour intervals.

In Example A-4, the SMF record interval on 05/25/2022 is 07:00:30 - 07:30:30 when JOB07760 (DEAPPD) user DPEAP was run.

Example A-4 SMF record type 82 subtype 31 (hex '001F')

```
Subtype=001F Crypto Usage Statistics
Written periodically to record crypto usage counts
25 May 2022 7:30:30.11
TME... 00293EA3 DTE... 0122145F SID... MVSF      SSI... 00000000 STY... 001F
INTVAL_START.. 05/25/2022 07:00:30.026731
INTVAL_END.... 05/25/2022 07:30:30.111713
USERID_AS..... DPEAP
USERID_TK.....
JOBID..... JOB07760
JOBNAME..... DPEAPPD
JOBNAME2.....
PLEXNAME..... MVSFPLEX
DOMAIN..... 0
ENG...CARD...7C01/93AACJPJ... 5
ENG...CARD...7C03/93AACJN6... 5
ALG...DES112..... 10
SRV...CSFENC..... 10
```

In JOB07761 (DEAPPE), user DPEAP was run at the same time as JOB07760 (see Example A-5).

Example A-5 SMF record type 82 subtype 31 (hex '001F')

```
Subtype=001F Crypto Usage Statistics
Written periodically to record crypto usage counts
25 May 2022 7:30:30.11
TME... 00293EA3 DTE... 0122145F SID... MVSF      SSI... 00000000 STY... 001F
INTVAL_START.. 05/25/2022 07:00:30.026731
INTVAL_END.... 05/25/2022 07:30:30.111713
USERID_AS..... DPEAP
USERID_TK.....
JOBID..... JOB07761
JOBNAME..... DPEAPPE
JOBNAME2.....
PLEXNAME..... MVSFPLEX
DOMAIN..... 0
ENG...CARD...7C01/93AACJPJ... 5
ENG...CARD...7C03/93AACJN6... 5
ALG...DES112..... 10
SRV...CSFENC..... 10
```

The information in the different subtypes varies. Subtypes 31 and 40 – 42 all contain job name and user ID; sub-types 44 – 46 are accumulated over user ID and key ID. For the ICSF service that is called CSFENC, we must find a subtype 44 (hex '002C') that maps to CSFENC for user DPEAP over the relevant period.

The usage count in subtype 44 records might be larger than identified in the subtype 31 records. In Example A-6, we can see a record that has 20 calls to CSFENC for user DPEAP in the relevant period of our application. This result corresponds with the two usage statistics records in which the two jobs in Example A-4 and Example A-5 had 10 calls to CSFENC each.

In some calls that were made to ICSF, the key label might not be present; rather, the key fingerprint or key check value is present to help identify a key.

Example A-6 Subtype 44 key usage event

```

Subtype=002C CCA Symmetric Key Usage Event
  Written for usage events related to symmetric CCA tokens
  25 May 2022 11:02:46.08
    TME... 003CADA0 DTE... 0122145F SID... MVSF      SSI... 00000000 STY... 002C
    STOD.. 05/25/2022 05:00:48.402960
    ETOD.. 05/25/2022 11:02:45.849556
    SRV... CSFENC
    USGC.. 20
    LBL... VDEKDESW3.00.500000.203704.IX0001                                DATA
    TOKFMT Fixed
    KALG.. DES
    KSEC.. Wrapped by MK
    CV.... '00007D0003600081'x (DATA*)
    TIV... 'C97A80A9'x
    KFP... 010105D5B74D
          ENCZ.. 'D5B74D'x
  End User Identity...
    USRI.. DPEAP

```

A key usage event record is available that relates to two job executions. The key label is identified as VDEKDESW3.00.500000.203704.IX0001. The key label and details can also be found in the IBM CAT GUI (see Figure A-7).

VDEKDESW3.00.500000.203704.IX0001

Key info

Algorithm: DES	Key type: DATA
Creation time: 2022-04-08 07:44:09.28	Version: 00
Update time: 1900-01-01 01:00:00.0	Wrap method: EW3
Key size: DOUBLE	

Details

KCV: D5B74DB6
 KCV method: ENC-ZERO
 Control vector: 00007D0003600081 7C927E758D7790AE

Attribute

Encrypted key and master key verification pattern (MKVP) are present.
 Control vector (CV) value in this token has been applied to the key.

Duplicate keys

No other keys with same key value

Figure A-7 Key label and details

A.3.2 Examples of finding key lifecycle events

Starting from the SDSF job listing that is shown in Figure A-6 on page 126, we use job ID JOB07756 as an example for cryptographic usage and key lifecycle events. For this example, we correlate SMF record type 82 subtypes 31 and 40.

JOB07756 is run by using the JCL member DPEAPDER (see Example A-7). Here, we find that program DKMSKSA calls DERKEYS.

Example A-7 JCL for DPEAPDER

```
//DPEAPDER JOB (9060-02292-01-33,LU2),'TEST DERKEYS',
//          MSGCLASS=T,CLASS=G,MSGLEVEL=(1,1)
/*JOBPARM S=MVSF
//RUNAPI   EXEC PGM=IKJEFT01,REGION=0M
//STEPLIB DD DISP=SHR,DSN=DPLMF.KSA0501X.LOAD
//          DD DISP=SHR,DSN=DPLMF.KSA0501X.LOADD
//          DD DSN=DB2FSYS.SDSNEXIT,DISP=SHR
//          DD DSN=DB2FSYS.SDSNLOAD,DISP=SHR
//SYSTSIN DD *
DSN SYST(DB2F)
RUN PROGRAM(DERKEYS) PLAN(KSA0501V)
END
```

For JOB07756 (DEAPDER, user DPEAP), we see in Example A-8 that the record covers the interval of 05/25/2022, 07:00:30 - 07:30:30.

Example A-8 SMF record type 82 subtype 31 (hex '001F')

```
Subtype=001F Crypto Usage Statistics
Written periodically to record crypto usage counts
25 May 2022 7:30:30.11
TME... 00293EA3 DTE... 0122145F SID... MVSF SSI... 00000000 STY... 001F
INTVAL_START.. 05/25/2022 07:00:30.026731
INTVAL_END.... 05/25/2022 07:30:30.111713
USERID_AS..... DPEAP
USERID_TK.....
JOBID..... JOB07756
JOBNAME..... DPEAPDER
JOBNAME2.....
PLEXNAME..... MVSFPLEX
DOMAIN..... 0
ENG...CARD...7C01/93AACJPJ... 20
ENG...CARD...7C03/93AACJN6... 21
ENG...CPACF... 1
ALG...DES112..... 7
ALG...DES168..... 51
ALG...SHA1..... 1
SRV...CSFKTB..... 8
SRV...CSFOWH..... 1
SRV...CSFDKG..... 8
SRV...CSFRKX..... 17
```

Among the ICSF services called in this job, CSFRKX is called 17 times during the execution. CSFRKX triggers a key lifecycle event, in this case subtype 40 (hex '0028') records are generated. These records are written shortly after the call occurs and is not an aggregated record as with the key usage event records. We can then search for a subtype 40 records in the timeframe of the job execution and for the job name DPEAPDER (see Example A-9).

Example A-9 SMF record type 82 subtype 40 (hex '0028')

```
Subtype=0028 CCA Symmetric Key Lifecycle Event
Written for lifecycle events related to symmetric CCA tokens
25 May 2022 7:01:41.30
TME... 00269B52 DTE... 0122145F SID... MVSF SSI... 00000000 STY... 0028
KEV... Key Exported
SRV... CSFRKX
LBL... VZMKDES.00.3000
EXPORTER
KFP... 01010562C123
ENCZ.. '62C123'x
TOKFMT Fixed
KALG.. DES
KSEC.. Wrapped by MK
CV.... '00417E0003600081'x (EXPORTER/OKEYXLAT)
TIV... '384479E0'x
ICSF Server Identity...
USRI.. CSF00000
GRPN.. CC
JBN... CSF
```

```

RST... 7:35:21.23
RSD... 24 May 2022
SUID.. 4040404040404040
End User Identity...
USRI.. DPEAP
GRPN.. DP
JBN... DPEAPDER
RST... 7:01:41.18
RSD... 25 May 2022
SUID.. 4040404040404040

```

The key label in this case is identified as VZMKDES.00.3000 and can be found in IBM CAT, as shown in Figure A-8.

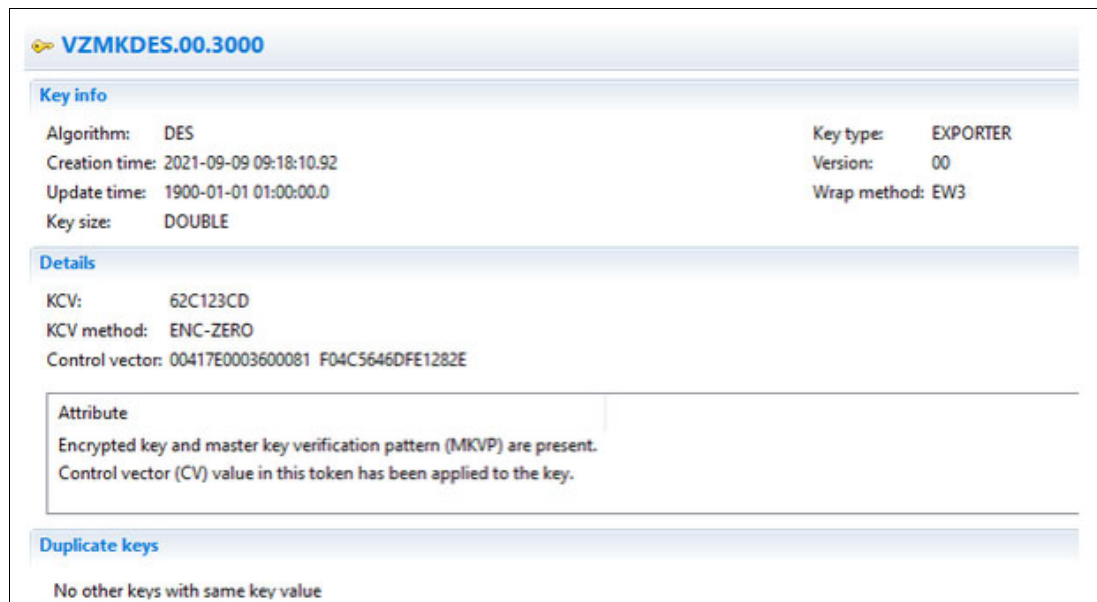


Figure A-8 IBM CAT - key label and details

A.3.3 Summary

We started with an ADDI scan of programs, DKMSKSA and DKMSRKX. Then, we identified two ICSF service calls, the jobs that performed them, and the cryptographic keys that were used in the ICSF service calls and key lifecycle events.

Searching through ICSF SMF records and SDSF job listings can be a significant undertaking and time consuming, depending on the use of cryptographic functions. A deep understanding of your JCL, applications, and programs is essential.

In addition, ICSF SMF records are not always written at the same time. In our environment, SMF type record 82 subtype 31 are written twice every hour (at top and bottom of the hour), and subtypes 40 – 42 are written as they occur. SMF record type 82 subtypes 44 – 46 are written at six-hour intervals, beginning at the time ICSF is started. The intervals at which the SMF records are written must be considered when identifying application and program use of ICSF service calls and their associated cryptographic material.



Generating quantum-safe keys

The examples in this appendix are REXX executables that can be used to generate quantum-safe keys that use CCA and PKCS#11.

This appendix includes the following topics:

- ▶ B.1, “CCA AES 256-bit key generation REXX sample” on page 134
- ▶ B.2, “PKCS #11 AES 256-bit key generation REXX sample” on page 137
- ▶ B.3, “CCA CRYSTALS-Dilithium key pair generation REXX sample” on page 139
- ▶ B.4, “PKCS #11 CRYSTALS-Dilithium key pair generation REXX sample” on page 142
- ▶ B.5, “CCA CRYSTALS-Kyber key pair generation REXX sample” on page 144
- ▶ B.6, “PKCS #11 CRYSTALS-Kyber key pair generation REXX sample” on page 147

B.1 CCA AES 256-bit key generation REXX sample

A CCA AES 256-bit key generation REXX sample is shown in Example B-1.

Example B-1 CCA AES 256-bit key generation REXX sample

```
/* rexx */
/*-----*/
/* Generate a secure CCA 256-bit AES CIPHER key */
/*-----*/

/* expected results */
ExpRC = '00000000'x ;
ExpRS = '00000000'x ;

/*-----*/
/* Build skeleton token with key usage and key management */
/*-----*/

KTB2_rule_array = 'INTERNAL' || ,
                  'AES'      ' ' || ,
                  'NO-KEY'   ' ' || ,
                  'CIPHER'   ' ' || ,
                  'ENCRYPT'   ' ' || ,
                  'DECRYPT'   ' ' || ,
                  'C-XLATE'   ' ' || ,
                  'ANY-MODE'   ' ' || ,
                  'NOEX-SYM'   ' ' || ,
                  'NOEX-RAW'   ' ' || ,
                  'NOEXUASY'   ' ' || ,
                  'NOEXAASY'   ' ' || ,
                  'NOEX-DES'   ' ' || ,
                  'NOEX-AES'   ' ' || ,
                  'NOEX-RSA'   ' ' || ,
                  'XPRTCPAC'

call CSNBKTB2

/*-----*/
/* Generate the AES key using the skeleton token from KTB2 */
/*-----*/
KGN2_Rule_Array = 'AES'      ' ' || ,
                  'OP'      ' ' || ,
KGN2_clear_key_Bit_Len = '00000100'x /* 256-bit */
KGN2_key_Type_1 = 'TOKEN'
KGN2_key_Type_2 = ''
KGN2_gen_key_1_Len = '000002D5'x
KGN2_gen_key_1 = left(KTB2_target_key_token,c2d(KGN2_gen_key_1_Len))

call CSNBKGN2

exit
```

```

/* ----- */
/* CSNBKTB2 - Key Token Build2 */
/*
/* Builds a variable-length AES skeleton token.
/*
/* See the ICSF Application Programmer's Guide for more details.
/* ----- */
CSNBKTB2:

    KTB2_rc          = 'ffffffff'x ;
    KTB2_rs          = 'ffffffff'x ;
    KTB2_exit_Length = '00000000'x ;
    KTB2_exit_Data   = '' ;
    KTB2_key_name_len = '00000000'x ;
    KTB2_key_name     = '' ;
    KTB2_user_data_Len = '00000000'x ;
    KTB2_user_data    = '' ;
    KTB2_token_data_Len = '00000000'x ;
    KTB2_token_data   = '' ;
    KTB2_clear_key    = '' ;
    KTB2_service_data = '' ;
    KTB2_service_data_Len = D2C(length(KTB2_service_data),4) ;
    KTB2_target_key_token_Len = d2c(725,4) ;
    KTB2_target_key_token = copies('00'x,c2d(KTB2_target_key_token_Len)) ;
    KTB2_clear_key_bit_Len = '00000000'x ;
    KTB2_Rule_count     = D2C(length(KTB2_rule_array)/8,4) ;

address linkpgm 'CSNBKTB2'
    'KTB2_rc'          'KTB2_rs'          ,
    'KTB2_exit_Length' 'KTB2_exit_Data' ,
    'KTB2_rule_count'  'KTB2_rule_array' ,
    'KTB2_clear_key_bit_Len' ,
    'KTB2_clear_key' ,
    'KTB2_key_name_Len' 'KTB2_key_name' ,
    'KTB2_user_data_Len' 'KTB2_user_data' ,
    'KTB2_token_data_Len' 'KTB2_token_data' ,
    'KTB2_service_data_Len' 'KTB2_service_data' ,
    'KTB2_target_key_token_Len' 'KTB2_target_key_token' ;

    KTB2_target_key_token = ,
        substr(KTB2_target_key_token,1,c2d(KTB2_target_key_token_Len))

    If (KTB2_RC <> ExprC) | (KTB2_RS <> ExprS) then
        do;
            say 'KTB2 failed : rc =' c2x(KTB2_RC) 'rs =' c2x(KTB2_RS)
        end;
    else
        say 'KTB2 successful : rc =' c2x(KTB2_RC) 'rs =' c2x(KTB2_RS)

return
/* ----- */
/* CSNBKGN - Key Generate */
/*

```

```

/* Generates either one or two DES or AES keys encrypted under a */
/* master key (internal form) or KEK (external form). */
/* */
/* See the ICSF Application Programmer's Guide for more details. */
/* ----- */

```

CSNBKGN2:

```

KGN2_rc          = 'ffffffff'x ;
KGN2_rs          = 'ffffffff'x ;
KGN2_Exit_Length = '00000000'x ;
KGN2_Exit_Data   = '' ;
KGN2_Rule_count  = D2C(length(KGN2_rule_array)/8,4)
KGN2_key_Name_1_Len = '00000000'x ;
KGN2_key_Name_1   = '' ;
KGN2_key_Name_2_Len = '00000000'x ;
KGN2_key_Name_2   = '' ;
KGN2_user_data_1_Len = '00000000'x ;
KGN2_user_data_1   = '' ;
KGN2_user_data_2_Len = '00000000'x ;
KGN2_user_data_2   = '' ;
KGN2_KEK_1_Len    = '00000000'x ;
KGN2_KEK_1        = '' ;
KGN2_KEK_2_Len    = '00000000'x ;
KGN2_KEK_2        = '' ;
KGN2_gen_key_2_Len = '00000000'x ;
KGN2_gen_key_2    = '' ;

```

```

address linkpgm 'CSNBKGN2'
    'KGN2_rc'          'KGN2_rs'          ,
    'KGN2_Exit_Length' 'KGN2_Exit_Data' ,
    'KGN2_Rule_Count'  'KGN2_Rule_Array' ,
    'KGN2_clear_key_Bit_Len' ,
    'KGN2_key_Type_1'  'KGN2_key_Type_2' ,
    'KGN2_key_Name_1_Len' 'KGN2_key_Name_1' ,
    'KGN2_key_Name_2_Len' 'KGN2_key_Name_2' ,
    'KGN2_user_data_1_Len' 'KGN2_user_data_1' ,
    'KGN2_user_data_2_Len' 'KGN2_user_data_2' ,
    'KGN2_KEK_1_Len'    'KGN2_KEK_1' ,
    'KGN2_KEK_2_Len'    'KGN2_KEK_2' ,
    'KGN2_gen_key_1_Len' 'KGN2_gen_key_1' ,
    'KGN2_gen_key_2_Len' 'KGN2_gen_key_2' ;

```

```

If (KGN2_RC <> ExpRC) | (KGN2_RS <> ExpRS) then
do;
    say 'KGN2 failed: rc =' c2x(KGN2_RC) 'rs =' c2x(KGN2_RS)
end;
else
    say 'KGN2 successful: rc =' c2x(KGN2_RC) 'rs =' c2x(KGN2_RS)

```

```

KGN2_gen_key_1 = substr(KGN2_gen_key_1,1,c2d(KGN2_gen_key_1_len))
KGN2_gen_key_2 = substr(KGN2_gen_key_2,1,c2d(KGN2_gen_key_2_len))

```

Return

B.2 PKCS #11 AES 256-bit key generation REXX sample

A PKCS #11 AES 256-bit key generation REXX sample is shown in Example B-2.

Example B-2 PKCS #11 AES 256-bit key generation REXX sample

```
/*rexex*/
/*-----*/
/* Generate a secure 256-bit PKCS #11 AES key */
/*-----*/
Call TCSetup

/* expected results */
ExpRC = '00000000'x ;
ExpRS = '00000000'x ;

/*-----*/
/* Generate the AES key using the attribute list */
/*-----*/

GSK_Handle      = Left('QSAFE.TEST.TOKEN',44) ;
GSK_AttrList    = '0007'x || , /* number attributes */
  CKA_CLASS      || '0004'x || CKO_SECRET_KEY || ,
  CKA_KEY_TYPE   || '0004'x || CKK_AES        || ,
  CKA_VALUE_LEN  || '0004'x || '00000020'x   || , /* AES 256-bit */
  CKA_TOKEN      || '0001'x || CK_TRUE        || ,
  CKA_IBM_SECURE || '0001'x || CK_TRUE        || ,
  CKA_ENCRYPT     || '0001'x || CK_TRUE        || ,
  CKA_DECRYPT     || '0001'x || CK_TRUE        || ,

Call CSFPGSK;

exit
/* ----- */
/* PKCS #11 Generate Secret Key */
/* Use the generate secret key callable service to generate a */
/* secret key or set of domain parameters. */
/* */
/* See the ICSF Application Programmer's Guide for more details. */
/* ----- */
CSFPGSK:
  GSK_RC          = 'FFFFFFFF'x ;
  GSK_RS          = 'FFFFFFFF'x ;
  GSK_Exit_Length = '00000000'x ;
  GSK_Exit_Data   = '' ;
  GSK_Rule_Count  = '00000001'x;
  GSK_Rule_Array  = 'KEY' ;
  GSK_Parms_List  = ''
  GSK_Parms_List_Length = '00000000'x

  GSK_AttrListLength = D2C( Length( GSK_AttrList ),4);
```

```

/* call GSK */
address linkpgm 'CSFPGSK'
    'GSK_RC'          'GSK_RS'          ,
    'GSK_Exit_Length' 'GSK_Exit_Data'   ,
    'GSK_Handle'      ,
    'GSK_Rule_Count'  'GSK_Rule_Array'   ,
    'GSK_AttrListLength' 'GSK_AttrList' ,
    'GSK_Parms_List_Length' 'GSK_Parms_List' ;

If (GSK_RC <> ExpRC) | (GSK_RS <> ExpRS) then
    say 'GSK failed: rc =' c2x(GSK_rc) 'rs =' c2x(GSK_rs) ;
else
    say 'GSK successful : rc =' c2x(GSK_rc) 'rs =' c2x(GSK_rs) ;

return

/* ----- */
/* ----- */
/* ----- */
TCSetup:

CKK_AES          = '0000001F'X

CKO_SECRET_KEY   = '00000004'X

CKA_CLASS        = '00000000'X
CKA_TOKEN        = '00000001'X
CKA_IBM_SECURE   = '80000006'X
CKA_KEY_TYPE     = '00000100'X
CKA_ENCRYPT       = '00000104'X;
CKA_DECRYPT       = '00000105'X;
CKA_VALUE_LEN    = '00000161'X

CK_TRUE          = '01'x
CK_FALSE         = '00'x

Return

EXIT;

```

B.3 CCA CRYSTALS-Dilithium key pair generation REXX sample

A CCA CRYSTALS-Dilithium key pair generation REXX sample is shown in Example B-3.

Example B-3 CCA CRYSTALS-Dilithium key pair generation REXX sample

```
/* REXX */

/*-----*/
/* Generate a secure CRYSTALS-Dilithium CCA key pair */
/*-----*/

/* expected results */
ExpRc = '00000000'x
ExpRs = '00000000'x

/*-----*/
/* Build skeleton token with key usage */
/*-----*/
PKB_Rule_Count = '00000002'x ;
PKB_Rule_Array = 'QSA-PAIR' ||,
                'U-DIGSIG'

/* CRYSTALS-Dilithium 87 Round 3 KVS */
PKB_KVS = '03'x ||, /* Alg Id */
          '00'x ||, /* clear key format */
          '0807'x ||, /* Alg param */
          '0000'x ||, /* clear key len */
          '0000'x /* Reserved */

/* CRYSTALS-Dilithium 65 Round 3 KVS */
/*
PKB_KVS = '03'x ||, /* Alg Id */
          '00'x ||, /* clear key format */
          '0605'x ||, /* Alg param */
          '0000'x ||, /* clear key len */
          '0000'x /* Reserved */
*/
call CSNDPKB

/*-----*/
/* Generate the Dilithium key pair using the skeleton token from PKB */
/*-----*/
PKG_Rule_Array = 'MASTER '
PKG_Skeleton_Key = PKB_Token;
PKG_Skeleton_Key_length = PKB_Token_length;

call CSNDPKG

Exit
```

```

/*-----*/
/* PKA Key Token Build - used to create PKA key tokens. */
/*-----*/
/* See the ICSF Application Programmer's Guide for more details. */
/*-----*/
CSNDPKB:

/* initialize parameter list */
PKB_Rc      = 'FFFFFFFF'x ;
PKB_Rs      = 'FFFFFFFF'x ;
Exit_Length = '00000000'x ;
Exit_Data   = '' ;
PKB_KVS_Length = d2c(length(PKB_KVS),4) ;
PKB_UAD_Length = '00000000'x ;
PKB_UAD      = '' ;
PKB_PrivName_Len = '00000000'x ;
PKB_PrivName   = '' ;
Reserved2_Length = '00000000'x ; Reserved2 = '' ;
Reserved3_Length = '00000000'x ; Reserved3 = '' ;
Reserved4_Length = '00000000'x ; Reserved4 = '' ;
Reserved5_Length = '00000000'x ; Reserved5 = '' ;
PKB_Token_Length = d2c(8000,4) ;
PKB_Token        = copies('00'x,8000) ;

/* call CSNDPKB */
address linkpgm 'CSNDPKB'
                'PKB_Rc'      'PKB_Rs'      ,
                'Exit_Length' 'Exit_Data'   ,
                'PKB_Rule_Count' 'PKB_Rule_Array' ,
                'PKB_KVS_Length' 'PKB_KVS'     ,
                'PKB_PrivName_Len' 'PKB_PrivName' ,
                'PKB_UAD_Length' 'PKB_UAD'     ,
                'Reserved2_Length' 'Reserved2' ,
                'Reserved3_Length' 'Reserved3' ,
                'Reserved4_Length' 'Reserved4' ,
                'Reserved5_Length' 'Reserved5' ,
                'PKB_Token_Length' 'PKB_Token' ;

if (PKB_Rc \= ExpRc | PKB_Rs \= ExpRs) then
    say 'PKB failed: rc =' c2x(PKB_Rc) 'rs =' c2x(PKB_Rs) ;
else
    do ;
        say 'PKB sucessful: rc =' c2x(PKB_Rc) 'rs =' c2x(PKB_Rs) ;
        PKB_Token = substr(PKB_Token,1,c2d(PKB_Token_Length)) ;
    end

return

/*-----*/
/* PKA Key Generate - Used to generate PKA key pairs */
/*-----*/
/* See the ICSF Application Programmer's Guide for more details. */
/*-----*/
CSNDPKG:

```

```

PKG_rc          = 'FFFFFFFF'x ;
PKG_rs          = 'FFFFFFFF'x ;
PKG_Exit_length = '00000000'x ;
PKG_Exit_Data   = '' ;
PKG_Rule_count   = d2c( length(PKG_Rule_Array)/8,4 )
PKG_Token_length = '00001F40'x ;
PKG_Token        = copies('00'x,c2d(PKG_token_length)) ;
PKG_Regen_data = ''
PKG_Regen_Data_length = d2c( length(PKG_Regen_data),4 )
PKG_Transport_Key_Id = ''

address linkpgm 'CSNDPKG' ,
               'PKG_rc'          'PKG_rs' ,
               'PKG_Exit_length' 'PKG_Exit_Data' ,
               'PKG_Rule_Count'   'PKG_Rule_Array' ,
               'PKG_Regen_Data_length' 'PKG_Regen_Data' ,
               'PKG_Skeleton_Key_length' 'PKG_Skeleton_Key' ,
               'PKG_Transport_Key_Id' ,
               'PKG_Token_length' 'PKG_Token' ;

if (PKG_rc \= ExpRc | PKG_rs \= ExpRs) then
  say 'PKG failed: rc =' c2x(PKG_rc) 'rs =' c2x(PKG_rs)
else
  Do;
  say 'PKG successful : rc =' c2x(PKG_rc) 'rs =' c2x(PKG_rs) ;
  PKG_Token = substr(PKG_Token,1,c2d(PKG_Token_length)) ;
  End;

Return

```

B.4 PKCS #11 CRYSTALS-Dilithium key pair generation REXX sample

A PKCS #11 CRYSTALS-Dilithium key pair generation REXX sample is shown in Example B-4.

Example B-4 PKCS #11 CRYSTALS-Dilithium key pair generation REXX sample

```
/* REXX */

/*-----*/
/* Generate a secure PKCS #11 Dilithium key pair */
/*-----*/

/* expected results */
ExpRC = '00000000'x ;
ExpRS = '00000000'x ;

Call TCSetup

GKP_Handle          = Left('QSAFE.TEST.TOKEN',44)

GKP_PrivKey_Attr_List = '0005'x||,
    CKA_CLASS        || '0004'x|| CKO_PRIVATE_KEY          ||,
    CKA_KEY_TYPE      || '0004'x|| CKK_IBM_DILITHIUM         ||,
    CKA_TOKEN          || '0001'x|| CK_TRUE                  ||,
    CKA_SIGN           || '0001'x|| CK_TRUE                  ||,
    CKA_IBM_SECURE     || '0001'x|| CK_TRUE

GKP_PubKey_Attr_List = '0005'x||,
    CKA_CLASS          || '0004'x|| CKO_PUBLIC_KEY           ||,
    CKA_KEY_TYPE        || '0004'x|| CKK_IBM_DILITHIUM        ||,
    CKA_IBM_DILITHIUM_MODE || '000D'x|| DER_OID_8_7_R3        ||,
    CKA_TOKEN           || '0001'x|| CK_TRUE                  ||,
    CKA_VERIFY          || '0001'x|| CK_TRUE

Call CSFPGKP;

Exit
/*-----*/
/* PKCS #11 Generate Key Pair */
/* Use the PKCS #11 Generate Key Pair callable service to generate */
/* an RSA, DSA, Elliptic Curve, Diffie-Hellman, Dilithium (LI2) or */
/* Kyber key pair. */
/* See the ICSF Application Programmer's Guide for more details. */
/*-----*/

CSFPGKP:
GKP_RC = 'FFFFFFFF'x
GKP_RS = 'FFFFFFFF'x
GKP_Exit_Length = '00000000'x
GKP_Exit_Data = ''
GKP_Rule_Count = '00000000'x
GKP_Rule_Array = ''
GKP_PubKey_Handle = copies(' ',44)
```

```

GKP_PrivKey_Handle = copies(' ',44)

GKP_PubKey_Attr_List_Length = D2C(Length(GKP_PubKey_Attr_List),4)
GKP_PrivKey_Attr_List_Length = D2C(Length(GKP_PrivKey_Attr_List),4)

address linkpgm 'CSFPGKP',
                'GKP_RC' 'GKP_RS',
                'GKP_Exit_Length' 'GKP_Exit_Data',
                'GKP_Handle',
                'GKP_Rule_Count' 'GKP_Rule_Array',
                'GKP_PubKey_Attr_List_Length',
                'GKP_PubKey_Attr_List',
                'GKP_PubKey_Handle',
                'GKP_PrivKey_Attr_List_Length',
                'GKP_PrivKey_Attr_List',
                'GKP_PrivKey_Handle'

    if (GKP_RC \= ExpRC | GKP_RS \= ExpRS) Then
        say 'GKP failed: rc =' c2x(GKP_rc) 'rs =' c2x(GKP_rs) ;
    else
        say 'GKP successful : rc =' c2x(GKP_rc) 'rs =' c2x(GKP_rs) ;

return;

/* ----- */
/* ----- */
/* ----- */
TCSSetup:

DER_OID_8_7_R3          = '060B2B0601040102820B070807'X

CKK_IBM_DILITHIUM        = '80010023'X

CKO_PUBLIC_KEY           = '00000002'X
CKO_PRIVATE_KEY          = '00000003'X

CKA_IBM_SECURE           = '80000006'X
CKA_KEY_TYPE              = '00000100'X
CKA_CLASS                 = '00000000'X
CKA_TOKEN                 = '00000001'X
CKA_IBM_DILITHIUM_MODE   = '80000010'X
CKA_SIGN                  = '00000108'X;
CKA_VERIFY                = '0000010A'X;

CK_TRUE                   = '01'x
CK_FALSE                  = '00'x
Return

EXIT;

```

B.5 CCA CRYSTALS-Kyber key pair generation REXX sample

A CCA CRYSTALS-Kyber key pair generation REXX sample is shown in Example B-5.

Example B-5 CCA CRYSTALS-Kyber key pair generation REXX sample

```
/* REXX */

/*-----*/
/* Generate a secure CRYSTALS-Kyber CCA key pair */
/*-----*/

/* expected results */
ExpRc = '00000000'x
ExpRs = '00000000'x

/*-----*/
/* Build skeleton token with key usage */
/*-----*/
PKB_Rule_Count = '00000003'x ;
PKB_Rule_Array = 'QSA-PAIR' ||,
                  'U-KEYENC' ||,
                  'U-DATENC'

/* CRYSTALS-Kyber 1024 Round 2 KVS */
PKB_KVS = '02'x ||, /* Alg Id */
          '00'x ||, /* clear key format */
          '1024'x ||, /* Alg param */
          '0000'x ||, /* clear key len */
          '0000'x /* Reserved */

call CSNDPKB

/*-----*/
/* Generate the Kyber key pair using the skeleton token from PKB */
/*-----*/
PKG_Rule_Array = 'MASTER '
PKG_Skeleton_Key = PKB_Token;
PKG_Skeleton_Key_length = PKB_Token_length;

call CSNDPKG

Exit
/*-----*/
/* PKA Key Token Build - used to create PKA key tokens. */
/*
/* See the ICSF Application Programmer's Guide for more details. */
/*-----*/
CSNDPKB:

/* initialize parameter list */
```

```

PKB_Rc          = 'FFFFFFFF'x ;
PKB_Rs          = 'FFFFFFFF'x ;
Exit_Length     = '00000000'x ;
Exit_Data       = '' ;
PKB_KVS_Length  = d2c(length(PKB_KVS),4) ;
PKB_UAD_Length  = '00000000'x ;
PKB_UAD         = '' ;
PKB_PrivName_Len = '00000000'x ;
PKB_PrivName     = '' ;
Reserved2_Length = '00000000'x ; Reserved2 = '' ;
Reserved3_Length = '00000000'x ; Reserved3 = '' ;
Reserved4_Length = '00000000'x ; Reserved4 = '' ;
Reserved5_Length = '00000000'x ; Reserved5 = '' ;
PKB_Token_Length = d2c(8000,4) ;
PKB_Token       = copies('00'x,8000) ;

/* call CSNDPKB */
address linkpgm 'CSNDPKB'
                'PKB_Rc'          'PKB_Rs'          ,
                'Exit_Length'     'Exit_Data'        ,
                'PKB_Rule_Count'  'PKB_Rule_Array'    ,
                'PKB_KVS_Length'  'PKB_KVS'          ,
                'PKB_PrivName_Len' 'PKB_PrivName'     ,
                'PKB_UAD_Length'  'PKB_UAD'          ,
                'Reserved2_Length' 'Reserved2'        ,
                'Reserved3_Length' 'Reserved3'        ,
                'Reserved4_Length' 'Reserved4'        ,
                'Reserved5_Length' 'Reserved5'        ,
                'PKB_Token_Length' 'PKB_Token'        ;

if (PKB_Rc \= ExpRc | PKB_Rs \= ExpRs) then
    say 'PKB failed: rc =' c2x(PKB_Rc) 'rs =' c2x(PKB_Rs) ;
else
    do ;
        say 'PKB sucessful: rc =' c2x(PKB_Rc) 'rs =' c2x(PKB_Rs) ;
        PKB_Token = substr(PKB_Token,1,c2d(PKB_Token_Length)) ;
    end

return

/* ----- */
/* PKA Key Generate - Used to generate PKA key pairs */
/* ----- */
/* See the ICSF Application Programmer's Guide for more details. */
/* ----- */
CSNDPKG:

PKG_rc          = 'FFFFFFFF'x ;
PKG_rs          = 'FFFFFFFF'x ;
PKG_Exit_length = '00000000'x ;
PKG_Exit_Data   = '' ;
PKG_Rule_count  = d2c( length(PKG_Rule_Array)/8,4 )
PKG_Token_length = '00001F40'x ;
PKG_Token       = copies('00'x,c2d(PKG_token_length)) ;

```

```

PKG_Regen_data = ''
PKG_Regen_Data_length = d2c( length(PKG_Regen_data),4 )
PKG_Transport_Key_Id = ''

address linkpgm 'CSNDPKG' ,
                'PKG_rc'          'PKG_rs' ,
                'PKG_Exit_length' 'PKG_Exit_Data' ,
                'PKG_Rule_Count'  'PKG_Rule_Array' ,
                'PKG_Regen_Data_length' 'PKG_Regen_Data' ,
                'PKG_Skeleton_Key_length' 'PKG_Skeleton_Key' ,
                'PKG_Transport_Key_Id' ,
                'PKG-Token_length' 'PKG-Token' ;

if (PKG_rc \= ExprC | PKG_rs \= ExprS) then
    say 'PKG failed: rc =' c2x(PKG_rc) 'rs =' c2x(PKG_rs)
else
    Do;
        say 'PKG successful : rc =' c2x(PKG_rc) 'rs =' c2x(PKG_rs) ;
        PKG-Token = substr(PKG-Token,1,c2d(PKG-Token_length)) ;
    End;

Return

```

B.6 PKCS #11 CRYSTALS-Kyber key pair generation REXX sample

A PKCS #11 CRYSTALS-Kyber key pair generation REXX sample is shown in Example B-6.

Example B-6 PKCS #11 CRYSTALS-Kyber key pair generation REXX sample

```
/* REXX */

Call TCSetup

/*-----*/
/* Generate a secure PKCS #11 Kyber key pair */
/*-----*/

/* expected results */
ExpRC = '00000000'x ;
ExpRS = '00000000'x ;

Call TCSETUP

GKP_Handle          = Left('QSAFE.TEST.TOKEN',44)

GKP_PrivKey_Attr_List = '0007'x||,
    CKA_CLASS        || '0004'x|| CKO_PRIVATE_KEY      ||,
    CKA_KEY_TYPE     || '0004'x|| CKK_IBM_KYBER         ||,
    CKA_TOKEN         || '0001'x|| CK_TRUE              ||,
    CKA_DERIVE        || '0001'x|| CK_TRUE              ||,
    CKA_DECRYPT        || '0001'x|| CK_TRUE              ||,
    CKA_UNWRAP        || '0001'x|| CK_TRUE              ||,
    CKA_IBM_SECURE    || '0001'x|| CK_TRUE

GKP_PubKey_Attr_List = '0007'x||,
    CKA_CLASS        || '0004'x|| CKO_PUBLIC_KEY        ||,
    CKA_KEY_TYPE     || '0004'x|| CKK_IBM_KYBER         ||,
    CKA_IBM_KYBER_MODE || '000D'x|| DER_OID_KYBER_1024_R2 ||,
    CKA_TOKEN         || '0001'x|| CK_TRUE              ||,
    CKA_WRAP          || '0001'x|| CK_TRUE              ||,
    CKA_DERIVE        || '0001'x|| CK_TRUE              ||,
    CKA_ENCRYPT        || '0001'x|| CK_TRUE

Call CSFPGKP;

Exit
/*-----*/
/* PKCS #11 Generate Key Pair */
/* Use the PKCS #11 Generate Key Pair callable service to generate */
/* an RSA, DSA, Elliptic Curve, Diffie-Hellman, Dilithium (LI2) or */
/* Kyber key pair. */
/*-----*/
/* See the ICSF Application Programmer's Guide for more details. */
/*-----*/
CSFPGKP:
    GKP_RC = 'FFFFFFFF'x
    GKP_RS = 'FFFFFFFF'x
```

```

GKP_Exit_Length = '00000000'x
GKP_Exit_Data = ''
GKP_Rule_Count = '00000000'x
GKP_Rule_Array = ''
GKP_PubKey_Handle = copies(' ',44)
GKP_PrivKey_Handle = copies(' ',44)

GKP_PubKey_Attr_List_Length = D2C(Length(GKP_PubKey_Attr_List),4)
GKP_PrivKey_Attr_List_Length = D2C(Length(GKP_PrivKey_Attr_List),4)

address linkpgm 'CSFPGKP',
    'GKP_RC' 'GKP_RS',
    'GKP_Exit_Length' 'GKP_Exit_Data',
    'GKP_Handle',
    'GKP_Rule_Count' 'GKP_Rule_Array',
    'GKP_PubKey_Attr_List_Length',
    'GKP_PubKey_Attr_List',
    'GKP_PubKey_Handle',
    'GKP_PrivKey_Attr_List_Length',
    'GKP_PrivKey_Attr_List',
    'GKP_PrivKey_Handle'

    if (GKP_RC \= ExpRC | GKP_RS \= ExpRS) Then
        say 'GKP failed: rc =' c2x(GKP_rc) 'rs =' c2x(GKP_rs) ;
    else
        say 'GKP successful : rc =' c2x(GKP_rc) 'rs =' c2x(GKP_rs) ;

return;

/* ----- */
/* ----- */
/* ----- */
TCSetup:

DER_OID_KYBER_1024_R2 = '060B2B0601040102820B050404'X;

CKK_IBM_KYBER          = '80010024'X;

CKO_PUBLIC_KEY         = '00000002'X
CKO_PRIVATE_KEY        = '00000003'X

CKA_IBM_SECURE         = '80000006'X
CKA_KEY_TYPE           = '00000100'X
CKA_CLASS              = '00000000'X
CKA_TOKEN              = '00000001'X
CKA_IBM_KYBER_MODE     = '8000000E'X;
CKA_ENCRYPT             = '00000104'X;
CKA_DECRYPT             = '00000105'X;
CKA_WRAP               = '00000106'X;
CKA_UNWRAP             = '00000107'X;
CKA_DERIVE             = '0000010C'X;

CK_TRUE                = '01'x
CK_FALSE               = '00'x

```

Return

EXIT;



Translating plain text into cipher text

The examples in this appendix are REXX executables that can be used to translate plain text into cipher text by using CCA and PKCS#11.

This appendix includes the following topics:

- ▶ C.1, “CCA ciphertext translation REXX sample” on page 152
- ▶ C.2, “PKCS #11 ciphertext translation REXX sample” on page 154

C.1 CCA ciphertext translation REXX sample

A CCA ciphertext translation REXX sample is shown in Example C-1.

Example C-1 CCA ciphertext translation from DES to AES REXX sample

```
/* REXX */

/*-----*/
/* Translate existing ciphertext to an AES 256-bit key */
/*-----*/

/* expected results */
ExpRc = '00000000'x
ExpRs = '00000000'x

/*-----*/
/* Call CSNBCTT2 to translate the existing ciphertext to AES */
/*-----*/
CTT2_Rule_Count      = '00000004'x
CTT2_rule_array      = 'I-CBC  '||'O-CBC  '||'IKEY-DES'||'OKEY-AES';
CTT2_cipher_text_in = 'E7861BBEEA363B3C40168B3174C15D31'x ;

/* Pass either the tokens or key labels of the encryption keys. */
CTT2_key_ID_in  = left('DATAENC#CTT2#DES#CIPHER',64)
CTT2_key_ID_out = left('DATAENC#CTT2#AES256#CIPHER',64) ;

Call CSNBCTT2

exit
/*-----*/
/* CipherText Translate2 */
/*
/* This callable service deciphers encrypted data (ciphertext) under
/* one cipher text translation key and reenciphers it under another
/* cipher text translation key without having the data appear in the
/* clear outside the cryptographic coprocessor.
/*
/* See the ICSF Application Programmer's Guide for more details.
/*-----*/
CSNBCTT2:

CTT2_rc          = 'FFFFFFFF'x ;
CTT2_rs          = 'FFFFFFFF'x ;
CTT2_Exit_Len    = '00000000'x ;
CTT2_Exit_Data   = '' ;
CTT2_IV_in_len   = '00000008'x
CTT2_IV_in       = '0000000000000000'x
CTT2_cipher_text_in_len = d2c(length(CTT2_cipher_text_in),4)
CTT2_chaining_vector_len = '00000080'x
CTT2_chaining_vector = copies('00'x,128)
CTT2_IV_out_len  = '00000010'x
CTT2_IV_out      = '0000000000000000'x
CTT2_rsv1_len    = '00000000'x
CTT2_rsv1        = ''
```

```

CTT2_rsv2_len      = '00000000'x
CTT2_rsv2          = ''
CTT2_key_ID_in_len = '00000040'x
CTT2_key_ID_out_len = '00000040'x
CTT2_cipher_text_out_len = d2c(length(CTT2_cipher_text_in),4)
CTT2_cipher_text_out = copies('00'x,c2d(CTT2_cipher_text_out_len))

```

```

address linkpgm 'CSNBCTT2'
    'CTT2_rc'          'CTT2_rs'          ,
    'CTT2_Exit_Len'    'CTT2_Exit_Data'    ,
    'CTT2_Rule_Count'  'CTT2_Rule_array'    ,
    'CTT2_key_ID_in_len' 'CTT2_key_ID_in'    ,
    'CTT2_IV_in_len'   'CTT2_IV_in'        ,
    'CTT2_cipher_text_in_len' 'CTT2_cipher_text_in',
    'CTT2_chaining_vector_len' 'CTT2_chaining_vector',
    'CTT2_key_ID_out_len' 'CTT2_key_ID_out'    ,
    'CTT2_IV_out_len'   'CTT2_IV_out'        ,
    'CTT2_cipher_text_out_len' 'CTT2_cipher_text_out',
    'CTT2_rsv1_len'     'CTT2_rsv1'          ,
    'CTT2_rsv2_len'     'CTT2_rsv2'          ;

```

```

if (CTT2_rc \= ExpRc | CTT2_rs \= ExpRs) then
    say 'CTT2 failed: rc=' c2x(CTT2_rc) 'rs =' c2x(CTT2_rs) ;
else
    say 'CTT2 successful: rc=' c2x(CTT2_rc) 'rs =' c2x(CTT2_rs) ;

```

```

return;

```

C.2 PKCS #11 ciphertext translation REXX sample

A PKCS #11 ciphertext translation REXX sample is shown in Example C-2.

Example C-2 PKCS #11 ciphertext translation from DES to AES REXX sample

```
/* rexx */

/*-----*/
/* Translate existing ciphertext to an AES 256-bit key */
/*-----*/

/* expected results */
ExpRC = '00000000'x ;
ExpRS = '00000000'x ;

SKR_Rule_Array = 'D-CBCPAD' || 'E-CBCPAD'

/*-----*/
/* Pass existing ciphertext and set IV according to the decryption */
/* key. For DES keys, IV length is 8. */
/*-----*/
SKR_dec_iv_length = '00000008'x;
SKR_dec_iv = copies('00'x,c2d(SKR_dec_iv_length) )
SKR_dec_text =,
'3AE0F4D65E911F061FED6FEB0CB84D6996A5623CADED94AEA3B8E2923F04E927'x ||,
'DADFD96CCDD8B5497442F6A75C82041AFE418D930AF4DE8B732A4D86C1D3F60EC'x ||,
'530BB9336A042B2A398FE650B8E38D2451D2427B904ED7B1'x
SKR_dec_text_length = d2c(length(SKR_dec_text),4)

/*-----*/
/* Set encryption IV length to 16 for AES */
/*-----*/
SKR_enc_iv_length = '00000010'x
SKR_enc_iv = copies('00'x,c2d(SKR_enc_iv_length))

/* Secure DES3 handle */
SKR_dec_handle = 'QSAFE.TEST.TOKEN' 00000001Y'
/* Secure AES 256 handle */
SKR_enc_handle = 'QSAFE.TEST.TOKEN' 00000002Y'

call CSFPSKR

exit
/* ----- */
/* PKCS #11 Secret Key Reencrypt */
/*
/* Use the PKCS #11 Secret Key Reencrypt callable service to
/* decrypt data and then reencrypt the data using secure secret
/* keys.
/*
/* See the ICSF Application Programmer's Guide for more details.
/* ----- */
CSFPSKR:
SKR_rc = 'FFFFFFFF'x ;
```



```

SKR_rs          = 'FFFFFFFF'x ;
SKR_Exit_Length = '00000000'x;
SKR_Exit_Data   = '';
SKR_Rule_Count  = '00000002'x;
SKR_chain_data_length = '00000000'x
SKR_chain_data   = '';
SKR_dec_text_id  = '00000000'x;
SKR_enc_text_length = D2C(1000,4);
SKR_enc_text     = COPIES('00'x,C2D(SKR_enc_text_length,4));
SKR_enc_text_id  = '00000000'x;

```

```

address linkpgm 'CSFPSKR'
    'SKR_rc'          'SKR_rs'          ,
    'SKR_Exit_Length' 'SKR_Exit_Data' ,
    'SKR_Rule_Count'  'SKR_Rule_Array',
    'SKR_dec_handle'  'SKR_enc_handle',
    'SKR_dec_iv_length' 'SKR_dec_iv'   ,
    'SKR_enc_iv_length' 'SKR_enc_iv'   ,
    'SKR_chain_data_length' 'SKR_chain_data',
    'SKR_dec_text_length' 'SKR_dec_text' ,
    'SKR_dec_text_id'    ,
    'SKR_enc_text_length' 'SKR_enc_text' ,
    'SKR_enc_text_id'    ;

```

```

if (SKR_rc \= ExprC | SKR_rs \= ExprS) then
    say 'SKR failed: rc =' c2x(SKR_rc) 'rs =' c2x(SKR_rs)
else
    say 'SKR successful rc =' c2x(SKR_rc) 'rs =' c2x(SKR_rs)
return;

```



D

Generating and verifying digital signatures

The examples in this appendix are REXX executables that can be used to generate and verify digital signatures using CCA and PKCS#11.

This appendix includes the following topics:

- ▶ D.1, “CCA CRYSTALS-Dilithium digital signature generation and verification REXX sample” on page 158
- ▶ D.2, “PKCS #11 CRYSTALS-Dilithium digital signature generation and verification REXX sample” on page 161

D.1 CCA CRYSTALS-Dilithium digital signature generation and verification REXX sample

A CCA CRYSTALS-Dilithium digital signature generation and verification REXX sample is shown in Example D-1.

Example D-1 CCA CRYSTALS-Dilithium digital signature generation and verification REXX sample

```
/* rexx */

/*-----*/
/* CRYSTALS-Dilithium Digital signature generation and verification */
/*-----*/

/* expected results */
ExpRc = '00000000'x ;
ExpRs = '00000000'x ;

/*-----*/
/* Call the CSNDDSG service passing the CRYSTALS-Dilithium private */
/* key. With a Crypto Express8S CCA Coprocessor, the message to be */
/* signed can be up to 15000 bytes. */
/*-----*/
DSG_Rule_Array = 'CRDL-DSA' ||,
                 'MESSAGE ' ||,
                 'CRDLHASH'
/* CRYSTALS-Dilithium 87 Round 3 Private key */
DSG_priv_key   = left('LI287R3.PRIV.0001',64)
DSG_data       = copies('G',15000) /* Message to Sign */

call CSNDDSG

/*-----*/
/* Call the CSNDDSG service passing the CRYSTALS-Dilithium public */
/* key. */
/*-----*/
DSV_Data       = DSG_data
DSV_Sig_Field   = DSG_sig_field
DSV_Rule_Array  = DSG_Rule_Array
/* CRYSTALS-Dilithium 87 Round 3 Public key */
DSV_pub_key    = left('LI287R3.PUB.0002',64)

call CSNDDSV

exit

/* ----- */
/* Digital Signature Generate */
/* ----- */
/* Use the Digital Signature Generate callable service to generate */
/* a digital signature using a PKA private key. */
/* ----- */
```

```

/* See the ICSF Application Programmer's Guide for more details.  */
/* ----- */
CSNDDSG:

DSG_rc          = 'FFFFFFFF'x ;
DSG_rs          = 'FFFFFFFF'x ;
DSG_Exit_Length = '00000000'x ;
DSG_Exit_Data   = '' ;
DSG_Data_Length = D2C( Length(DSG_Data),4 );
DSG_Sig_Field_Length = '00001388'x ;
DSG_Sig_Bit_Length = '00000800'x ;
DSG_Sig_Field    = copies('00'x,c2d(DSG_Sig_field_length))
DSG_rule_count   = d2c( length(DSG_rule_array)/8,4 )
DSG_priv_key_length = d2c( length(DSG_priv_key),4 )

address linkpgm 'CSNDDSG'
          'DSG_rc'          'DSG_rs'          ,
          'DSG_Exit_Length' 'DSG_Exit_Data' ,
          'DSG_Rule_Count'  'DSG_Rule_Array' ,
          'DSG_priv_key_length' 'DSG_priv_key' ,
          'DSG_data_length'  'DSG_data'      ,
          'DSG_sig_field_length' ,
          'DSG_sig_bit_length' ,
          'DSG_sig_field'      ;

DSG_sig_field = substr(DSG_sig_field,1,c2d(DSG_sig_field_length))

if (DSG_rc \= ExpRc | DSG_rs \= ExpRs) then
  say 'DSG: failed: rc =' c2x(DSG_rc) 'rs =' c2x(DSG_rs)
else
  say 'DSG successful : rc =' c2x(DSG_rc) 'rs =' c2x(DSG_rs) ;

return;

/* ----- */
/* Digital Signature Verify */
/* ----- */
/* Use the Digital Signature Verify callable service to verify a */
/* digital signature using a PKA public key. */
/* ----- */
/* See the ICSF Application Programmer's Guide for more details. */
/* ----- */
CSNDDSV:

DSV_rc          = 'FFFFFFFF'x ;
DSV_rs          = 'FFFFFFFF'x ;
DSV_Exit_Length = '00000000'x ;
DSV_Exit_Data   = '' ;
DSV_Data_Length = D2C( Length(DSV_Data),4 );
DSV_Sig_Field_Length = d2c( length(DSV_sig_field),4 )

DSV_rule_count   = d2c( length(DSV_rule_array)/8,4 )
DSV_pub_key_length = d2c( length(DSV_pub_key),4 )

```

```

address linkpgm 'CSNDDSV'
      'DSV_rc'      'DSV_rs'
      'DSV_Exit_Length' 'DSV_Exit_Data'
      'DSV_Rule_Count'  'DSV_Rule_Array'
      'DSV_pub_key_length' 'DSV_pub_key'
      'DSV_data_length'   'DSV_data'
      'DSV_sig_field_length'
      'DSV_sig_field'

```

```

if DSV_rc \= ExpRc | DSV_rs \= ExpRs then
  say 'DSV failed: rc =' c2x(DSV_rc) 'rs =' c2x(DSV_rs)
else
  say 'DSV successful : rc =' c2x(DSV_rc) 'rs =' c2x(DSV_rs) ;

```

```

return;

```

D.2 PKCS #11 CRYSTALS-Dilithium digital signature generation and verification REXX sample

A PKCS #11 CRYSTALS-Dilithium digital signature generation and verification REXX sample is shown in Example D-2.

Example D-2 PKCS #11 CRYSTALS-Dilithium digital signature generation and verification REXX

```
/* rexx */

/*-----*/
/* CRYSTALS-Dilithium Digital signature generation and verification */
/*-----*/

/* expected results */
ExpRC = '00000000'x ;
ExpRS = '00000000'x ;

/*-----*/
/* Call the CSFPPKS service passing the CRYSTALS-Dilithium private */
/* key handle to generate the digital signature. */
/*-----*/
PKS_Rule_Array      = 'LI2      '
PKS_Key_Handle      = 'QSAFE.TEST.TOKEN          00000003Y'
PKS_Cipher_Value    = Copies('A',128)
PKS_Cipher_Value_Length = D2C( Length(PKS_Cipher_Value),4 );
PKS_Clear_Value_Length = D2C(4596,4);
PKS_Clear_Value     = Copies('00'x, C2D(PKS_Clear_Value_Length) )

Call CSFPPKS

/*-----*/
/* Call the CSFPPKV service passing the CRYSTALS-Dilithium public */
/* key handle to verify the digital signature. */
/*-----*/
PKV_Key_Handle      = 'QSAFE.TEST.TOKEN          00000002Y'

Call CSFPPKV

exit
/* ----- */
/* PKCS #11 Private Key Sign */
/* ----- */
/* Used to sign data using an ECC, RSA, DSA, or CRYSTALS-Dilithium */
/* private key. */
/* ----- */
CSFPPKS:

PKS_RC              = 'FFFFFFFF'x ;
PKS_RS              = 'FFFFFFFF'x ;
PKS_Exit_Length     = '00000000'x ;
PKS_Exit_Data       = '' ;

PKS_Rule_Count = d2c( length(PKS_Rule_Array)/8,4 )
```

```

address linkpgm 'CSFPPKS'
    'PKS_rc'
    'PKS_rs'
    'PKS_Exit_Length'
    'PKS_Exit_Data'
    'PKS_Rule_Count'
    'PKS_Rule_Array'
    'PKS_Cipher_Value_Length'
    'PKS_Cipher_Value'
    'PKS_Key_Handle'
    'PKS_Clear_Value_Length'
    'PKS_Clear_Value'

PKS_Clear_value = ,
    substr(PKS_clear_value,1,c2d(PKS_Clear_value_length))

if (PKS_RC \= ExpRC | PKS_RS \= ExpRS) Then
    say 'PKS Failed : rc =' c2x(PKS_RC) 'rs =' c2x(PKS_RS) ;
else
    say 'PKS Successful : rc =' c2x(PKS_RC) 'rs =' c2x(PKS_RS) ;
return;
/* ----- */
/* PKCS #11 Public Key Verify */
/*
/* Used to verify a signature using an ECC, RSA, DSA, or
/* CRYSTALS-Dilithium public key.
/* ----- */
CSFPPKV:

PKV_RC          = 'FFFFFFFF'x ;
PKV_RS          = 'FFFFFFFF'x ;
PKV_Exit_Length = '00000000'x ;
PKV_Exit_Data   = '';
PKV_Cipher_Value_length = PKS_Cipher_Value_length
PKV_Cipher_Value = PKS_Cipher_Value
PKV_Clear_Value  = PKS_Clear_Value
PKV_Clear_Value_length = PKS_Clear_Value_length
PKV_Rule_Array   = PKS_Rule_Array
PKV_Rule_Count   = d2c( length(PKV_rule_Array)/8,4 )

address linkpgm 'CSFPPKV'
    'PKV_RC'
    'PKV_RS'
    'PKV_Exit_Length'
    'PKV_Exit_Data'
    'PKV_Rule_Count'
    'PKV_Rule_Array'
    'PKV_Clear_Value_Length' ,
    'PKV_Clear_Value'
    'PKV_Key_Handle'
    'PKV_Cipher_Value_length' ,
    'PKV_Cipher_Value' ;

```



```
PKV_Cipher_value = ,
    substr(pkv_cipher_value,1,c2d(PKV_Cipher_value_length))

if (PKV_RC \= ExpRC | PKV_RS \= ExpRS) Then
    say 'PKV Failed : rc =' c2x(PKV_RC) 'rs =' c2x(PKV_RS) ;
else
    say 'PKV successful : rc =' c2x(PKV_RC) 'rs =' c2x(PKV_RS) ;

return;
```



Creating a hybrid quantum-safe key exchange

The examples in this appendix are REXX executables that can be used to create a hybrid quantum-safe key exchange using CCA and PKCS#11.

This appendix includes the following topics:

- ▶ E.1, “CCA hybrid quantum-safe key exchange scheme REXX sample” on page 166
- ▶ E.2, “PKCS #11 hybrid quantum-safe key exchange scheme REXX sample” on page 176

E.1 CCA hybrid quantum-safe key exchange scheme REXX sample

A CCA hybrid quantum-safe key exchange scheme REXX sample is shown in Example E-1.

Example E-1 CCA Hybrid Quantum-safe key exchange scheme REXX sample

```
/* REXX */

/*-----*/
/* CCA Hybrid Quantum-safe Key exchange scheme */
/*-----*/
/* PKE will require ACP '0083'x */
/* EDH will require ACP '035D'x */
/*-----*/

CALL INITIALIZE

/* expected results */
Exp_rc = '00000000'x
Exp_rs = '00000000'x

/* global parameters */
exit_data_length = '00000000'x
exit_data = ''

/* PKB parameters */
private_name = ''
user_assoc_data = ''

/* PKE parameters */
PKE_rule_array = 'ZERO-PAD'
PKE_keyvalue = ''
sym_key_identifier = ''

/* KYT2 parameters */
kek_identifier = ''

/*-----*/
/* Create ALICE's keys */
/*-----*/

Say "Generating Alice's Kyber key pair..."

/*-----*/
/* Build Kyber skeleton token with U-DATENC key usage flag */
/*-----*/
PKB_rule_array = 'QSA-PAIR' || 'U-DATENC'
kvs = '02'x ||, /* algorithm identifier */
      '00'x ||, /* clear key format skeleton */
      '1024'x ||, /* algorithm parameter */
      '0000'x ||, /* clear key length */
      '0000'x /* reserved */
CALL CSNDPKB
```

```

/*-----*/
/* Generate Kyber key pair using built skeleton token */
/*-----*/
PKG_rule_array = 'master '
CALL CSNDPKG

ALICE_Kyber_pvt = PKG_token

/*-----*/
/* Extract Kyber public key from Kyber private key token */
/*-----*/
PKX_source_key = PKG_token
CALL CSNDPKX

ALICE_Kyber_publ = PKX_token

/*-----*/
/* Build ECC skeleton token with KEY-MGMT key usage flag */
/*-----*/
Say "Generating Alice's ECC key pair..."
PKB_rule_array = 'ECC-PAIR' || 'KEY-MGMT'
kvs             = '00'x ||, /* Prime curve */
                  '00'x ||, /* reserved */
                  '0180'x ||, /* 384 bits */
                  '0000'x ||, /* pvt key length */
                  '0000'x /* pub key length */
CALL CSNDPKB

/*-----*/
/* Generate ECC key pair using built skeleton token */
/*-----*/
PKG_rule_array = 'master '
CALL CSNDPKG

ALICE_ECC_pvt = PKG_token

/*-----*/
/* Extract ECC public key from ECC private key token */
/*-----*/
PKX_source_key = PKG_token
CALL CSNDPKX

ALICE_ECC_publ = PKX_token

/*-----*/
/* Create BOB's keys */
/*-----*/

/*-----*/
/* Build ECC skeleton token with KEY-MGMT key usage flag */
/*-----*/
Say "Generating Bob's ECC key pair..."

PKB_rule_array = 'ECC-PAIR' || 'KEY-MGMT'

```

```

kvs          = '00'x ||, /* Prime curve */
              '00'x ||, /* reserved */
              '0180'x ||, /* 384 bits */
              '0000'x ||, /* pvt key length */
              '0000'x /* pub key length */

CALL CSNDPKB

/*-----*/
/* Generate ECC key pair using built skeleton token */
/*-----*/
PKG_rule_array = 'master '
CALL CSNDPKG

BOB_ECC_pvt    = PKG_token

/*-----*/
/* Extract ECC public key from ECC private key token */
/*-----*/
PKX_source_key = PKG_token
CALL CSNDPKX

BOB_ECC_pub1   = PKG_token

/*-----*/
/* BOB creates the shared-key derivation input */
/*-----*/
PKE_rule_array = 'ZERO-PAD' || 'RANDOM '
PKE_keyvalue   = '010101010101010102020202020202'x ||,
                '000000000000000000000000000000'x
sym_key_identifier = BOB_AES_CIPHER_key_token
public_key_identifier = ALICE_KYBER_pub1
CALL CSNDPKE

/*-----*/
/* BOB completes the shared-key derivation */
/*-----*/
KYBER_enciphered_PKE_keyvalue = enciphered_PKE_keyvalue
sym_enciphered_PKE_keyvalue   = PKE_keyvalue

EDH_rule_array = 'DERIV01' || 'KEY-AES' || 'QSA-ECDH' || 'IHKEYAES'
private_key_identifier = BOB_ECC_pvt
private_kek_identifier = ''
public_key_identifier  = ALICE_ECC_pub1
hybrid_key_identifier  = BOB_AES_CIPHER_key_token
party_identifier       = 'Party#Identifier'
key_bit_length         = d2c(192,4)
initialization_vector  = '010101010101010102020202020202'x
hybrid_ciphertext      = sym_enciphered_PKE_keyvalue
output_kek_identifier  = ''
output_key_identifier  = AES_CIPHER_skeleton
CALL CSNDEDH

/*-----*/
/* A Key check value (KCV) is computed over BOBs shared-key */
/*-----*/

```

```

KYT2_rule_array = 'AES      ' || 'GENERATE' || 'CMACZERO' ;
key_identifier   = output_key_identifier
CALL CSNBKYT2
KYT2_kcv_BOB = KYT2_kcv

/*-----*/
/* Alice completes the shared-key derivation */
/*-----*/
EDH_rule_array = 'DERIV01 ' || 'KEY-AES ' || 'QSA-ECDH' || 'IHKEYKYB'
private_key_identifier = ALICE_ECC_pvt
private_kek_identifier = ''
public_key_identifier  = BOB_ECC_publ
hybrid_key_identifier  = ALICE_Kyber_pvt
party_identifier       = 'Party#Identifier'
key_bit_length         = d2c(192,4)
initialization_vector  = ''
hybrid_ciphertext      = KYBER_enciphered_PKE_keyvalue
output_kek_identifier  = ''
output_key_identifier   = AES_CIPHER_skeleton
CALL CSNDEDH
/*-----*/
/* A Key check value (KCV) is computed over Alice's */
/* shared-key */
/*-----*/
key_identifier = output_key_identifier
CALL CSNBKYT2
KYT2_kcv_ALICE = KYT2_kcv

/*-----*/
/* Verify that both Alice and Bobs shared-keys are identical */
/*-----*/
IF KYT2_kcv_ALICE = KYT2_kcv_BOB THEN SAY 'TESTCASE SUCCESSFUL'

Exit;
/*-----*/
/* PKA Key Token Build - used to create PKA key tokens. */
/* */
/* See the ICSF Application Programmer's Guide for more details. */
/*-----*/
CSNDPKB:

PKB_rc          = 'FFFFFFFF'x
PKB_rs          = 'FFFFFFFF'x
exit_data_length = '00000000'x
exit_data       = ''
PKB_rule_count  = d2c(length(PKB_rule_array)/8,4)
kvs_length      = d2c(length(kvs),4)
private_name_length = d2c(length(private_name),4)
user_assoc_data_length = d2c(length(user_assoc_data),4)
key_deriv_data_length = '00000000'x /* valid only with ECC-VER1 */
key_deriv_data   = ''
reserved_field3_length = '00000000'x
reserved_field3    = ''
reserved_field4_length = '00000000'x
reserved_field4     = ''

```

```

reserved_field5_length = '00000000'x
reserved_field5        = ''
PKB_token_length       = d2c(6500,4) /* max */
PKB_token              = d2c(0,6500)

ADDRESS LINKPGM 'CSNDPKB' ,
                'PKB_rc'          'PKB_rs' ,
                'exit_data_length' 'exit_data' ,
                'PKB_rule_count'   'PKB_rule_array' ,
                'kvs_length'       'kvs' ,
                'private_name_length' 'private_name' ,
                'user_assoc_data_length' 'user_assoc_data' ,
                'key_deriv_data_length' 'key_deriv_data' ,
                'reserved_field3_length' 'reserved_field3' ,
                'reserved_field4_length' 'reserved_field4' ,
                'reserved_field5_length' 'reserved_field5' ,
                'PKB_token_length'   'PKB_token'

IF PKB_rc \= Exp_rc | PKB_rs \= Exp_rs THEN
  SAY 'PKB FAILED rc =' c2x(PKB_rc) 'rs =' c2x(PKB_rs)
ELSE
  DO
    SAY 'PKB successful: rc =' c2x(PKB_rc) 'rs =' c2x(PKB_rs)
    PKB_token = SUBSTR(PKB_token,1,c2d(PKB_token_length))
  END

SAY
RETURN

/* ----- */
/* PKA Key Generate - Used to generate PKA key pairs. */
/* ----- */
/* See the ICSF Application Programmer's Guide for more details. */
/* ----- */
CSNDPKG:

PKG_rc          = 'FFFFFFFF'x ;
PKG_rs          = 'FFFFFFFF'x ;
PKG_rule_count  = d2c(length(PKG_rule_array)/8,4) ;
regeneration_data_length = '00000000'x ;
regeneration_data = '' ;
skeleton_key_id_length = PKB_token_length ;
skeleton_key_id      = PKB_token ;
transport_key_id     = d2c(0,64) ;
PKG_token_length    = d2c(6500,4) ;
PKG_token          = copies('00'x,6500) ;

ADDRESS LINKPGM 'CSNDPKG' ,
                'PKG_rc'          'PKG_rs' ,
                'exit_data_length' 'exit_data' ,
                'PKG_rule_count'   'PKG_rule_array' ,
                'regeneration_data_length' 'regeneration_data' ,
                'skeleton_key_id_length' 'skeleton_key_id' ,
                'transport_key_id' ,
                'PKG_token_length'   'PKG_token'

```



```

IF PKG_rc \= Exp_rc | PKG_rs \= Exp_rs THEN
    SAY 'PKG FAILED rc =' c2x(PKG_rc) 'rs =' c2x(PKG_rs)
ELSE
    DO
        SAY 'PKG successful: rc =' c2x(PKG_rc) 'rs =' c2x(PKG_rs)
        PKG_token = SUBSTR(PKG_token,1,c2d(PKG_token_length))
    END

SAY
RETURN

/*-----*/
/* PKA Public Key Extract */
/*
/* Extracts a PKA public key token from a PKA internal (operational)*/
/* or external (importable) private key token. */
/*
/* See the ICSF Application Programmer's Guide for more details. */
/*-----*/
CSNDPKX:

PKX_rc          = 'FFFFFFFF'x ;
PKX_rs          = 'FFFFFFFF'x ;
PKX_rule_array_count = '00000000'x ;
PKX_rule_array   = '' ;
PKX_source_key_length = d2c(length(PKX_source_key),4) ;
PKX_token_length  = d2c(6500,4) ;
PKX_token        = copies('00'x,6500) ;

ADDRESS LINKPGM 'CSNDPKX' ,
               'PKX_rc' ,
               'PKX_rs' ,
               'exit_data_length' ,
               'exit_data' ,
               'PKX_rule_array_count' ,
               'PKX_rule_array' ,
               'PKX_source_key_length' ,
               'PKX_source_key' ,
               'PKX_token_length' ,
               'PKX_token'

IF PKX_rc /= Exp_rc | PKX_rs /= Exp_rs THEN
    DO ;
        SAY 'PKX FAILED rc =' c2x(PKX_rc) 'rs =' c2x(PKX_rs)
    END ;
ELSE
    DO ;
        SAY 'PKX successful: rc =' c2x(PKX_rc) 'rs =' c2x(PKX_rs)
        PKX_token = ,
            SUBSTR(PKX_token,1,c2d(PKX_token_length))
    END
SAY
RETURN

```

```

/* ----- */
/* PKA Encrypt */
/* */
/* Creates and encrypts derivation input */
/* */
/* See the ICSF Application Programmer's Guide for more details. */
/* ----- */
CSNDPKE:

PKE_rc = 'FFFFFFFF'x
PKE_rs = 'FFFFFFFF'x
exit_data_length = '00000000'x
exit_data = ''
PKE_rule_array_count = d2c(length(PKE_rule_array)/8,4)
PKE_keyvalue_length = d2c(length(PKE_keyvalue),4)
sym_key_identifier_length = d2c(length(sym_key_identifier),4)
public_key_identifier_length = d2c(length(public_key_identifier),4)
enciphered_PKE_keyvalue_length = d2c(1568,4)
enciphered_PKE_keyvalue = d2c(0,1568)

ADDRESS LINKPGM 'CSNDPKE' ,
                'PKE_rc' ,
                'PKE_rs' ,
                'exit_data_length' ,
                'exit_data' ,
                'PKE_rule_array_count' ,
                'PKE_rule_array' ,
                'PKE_keyvalue_length' ,
                'PKE_keyvalue' ,
                'sym_key_identifier_length' ,
                'sym_key_identifier' ,
                'public_key_identifier_length' ,
                'public_key_identifier' ,
                'enciphered_PKE_keyvalue_length' ,
                'enciphered_PKE_keyvalue' ;

IF PKE_rc /= Exp_rc | PKE_rs /= Exp_rs THEN
  SAY 'PKE FAILED rc=' c2x(PKE_rc) 'rs =' c2x(PKE_rs) ;
ELSE
  DO
    enciphered_PKE_keyvalue = ,
      substr(enciphered_PKE_keyvalue,1,c2d(enciphered_PKE_keyvalue_length))
    SAY 'PKE successful rc=' c2x(PKE_rc) 'rs =' c2x(PKE_rs) ;
  END
SAY
RETURN

/* ----- */
/* ECC Diffie-Hellman */
/* */
/* Generates Z value from D-H process. Derives the shared-key using */
/* Z and rand-32 from PKE. */

```

```

/*                                                                 */
/* See the ICSF Application Programmer's Guide for more details.  */
/* -----*/
CSNDEDH:

EDH_rc = 'FFFFFFF'x
EDH_rs = 'FFFFFFF'x
exit_data_length = '00000000'x
exit_data = ''
EDH_rule_array_count = d2c(length(EDH_rule_array)/8,4)
private_key_identifier_length = d2c(length(private_key_identifier),4)
private_kek_identifier_length = d2c(length(private_kek_identifier),4)
public_key_identifier_length = d2c(length(public_key_identifier),4)
hybrid_key_identifier_length = d2c(length(hybrid_key_identifier),4)
party_identifier_length = d2c(length(party_identifier),4)
initialization_vector_length = d2c(length(initialization_vector),4)
hybrid_ciphertext_length = d2c(length(hybrid_ciphertext),4)
reserved3_length = '00000000'x
reserved3 = ''
reserved4_length = '00000000'x
reserved4 = ''
reserved5_length = '00000000'x
reserved5 = ''
output_kek_identifier_length = d2c(length(output_kek_identifier),4)
output_key_identifier_length = d2c(900,4)
output_key_identifier = left(output_key_identifier,900)

ADDRESS LINKPGM 'CSNDEDH' ,
                'EDH_rc' ,
                'EDH_rs' ,
                'exit_data_length' ,
                'exit_data' ,
                'EDH_rule_array_count' ,
                'EDH_rule_array' ,
                'private_key_identifier_length' ,
                'private_key_identifier' ,
                'private_kek_identifier_length' ,
                'private_kek_identifier' ,
                'public_key_identifier_length' ,
                'public_key_identifier' ,
                'hybrid_key_identifier_length' ,
                'hybrid_key_identifier' ,
                'party_identifier_length' ,
                'party_identifier' ,
                'key_bit_length' ,
                'initialization_vector_length' ,
                'initialization_vector' ,
                'hybrid_ciphertext_length' ,
                'hybrid_ciphertext' ,
                'reserved3_length' ,
                'reserved3' ,
                'reserved4_length' ,
                'reserved4' ,
                'reserved5_length' ,
                'reserved5' ,

```

```

        'output_kek_identifier_length' ,
        'output_kek_identifier' ,
        'output_key_identifier_length' ,
        'output_key_identifier' ;

IF EDH_rc /= Exp_rc | EDH_rs /= Exp_rs THEN
    SAY 'EDH FAILED rc =' c2x(EDH_rc) 'rs =' c2x(EDH_rs)
ELSE
    DO
        SAY 'EDH successful: rc =' c2x(EDH_rc) 'rs =' c2x(EDH_rs)
        output_key_identifier = ,
            substr(output_key_identifier,1,c2d(output_key_identifier_length))
    END
SAY
RETURN

/*-----*/
/* Key Test2 */
/* */
/* Generate or verify a secure, cryptographic verification pattern */
/* (also referred to as a key check value) for AES, DES and HMAC */
/* keys. */
/*-----*/
CSNBKYT2:

KYT2_rc = 'FFFFFFFF'x ;
KYT2_rs = 'FFFFFFFF'x ;
KYT2_rule_array_count = d2c(length(KYT2_rule_array)/8,4) ;
key_identifier_length = d2c(length(key_identifier),4) ;
kek_identifier_length = d2c(length(kek_identifier),4) ;
reserved_length = d2c(0,4) ;
reserved = '' ;
KYT2_kcv_length = d2c(8,4) ;
KYT2_kcv = d2c(0,c2d(KYT2_kcv_length)) ;

ADDRESS LINKPGM 'CSNBKYT2'
        'KYT2_rc' 'KYT2_rs' ,
        'exit_data_length' 'exit_data' ,
        'KYT2_rule_array_count' 'KYT2_rule_array' ,
        'key_identifier_length' 'key_identifier' ,
        'kek_identifier_length' 'kek_identifier' ,
        'reserved_length' 'reserved' ,
        'KYT2_kcv_length' 'KYT2_kcv' ;

IF KYT2_rc /= Exp_rc | KYT2_rs /= Exp_rs THEN
    SAY 'KYT2 failed: rc =' c2x(KYT2_rc) 'rs =' c2x(KYT2_rs) ;
ELSE
    SAY 'KYT2_kcv:' c2x(KYT2_kcv) ;

RETURN;

/* ----- */
INITIALIZE:

BOB_AES_CIPHER_key_token = ,

```

```
'010000DA0500000003012058C870E9D3194F000000000000000020200000100'x||,
'007440001A0002400002000102C000000003E000000005054145532443495048'x||,
'4552233139324249544034332E32432E3136202020202020202020202020'x||,
'202020202020202020202020202020202020202020202020C1C5E240C3C9D7C8'x||,
'C5D940F1F9F2C2C9E340F4F36DF2C36DF1F6E2219F0ED611C48D338927427F2D'x||,
'141BB9EA9B5B198C98E141BFDD0FFC7B403B8F68620E8744CC92E321354C0707'x||,
'A2CC1E32C835563FDB749C76FF3A0CB32DB0667FA1CA77E8F1B1'x
```

```
/* symmetric key skeletons */
```

```
AES_CIPHER_SKELETON = ,
```

```
'01000038050000000000000000000000000000000000000020200000100'x||,
'001A00000000000000002000102C000000003E0000000000'x
```

```
RETURN
```

E.2 PKCS #11 hybrid quantum-safe key exchange scheme REXX sample

A PKCS #11 hybrid quantum-safe key exchange scheme REXX sample is shown in Example E-2.

Example E-2 PKCS #11 Hybrid Quantum-safe key exchange scheme REXX sample

```
/* REXX */

/*****
/* PKCS #11 Hybrid Quantum-safe Key Exchange Scheme
*****/
SIGNAL ON NOVALUE;

Call TCSETUP

/*****
/* Common test data
*****/
/* expected results */
ExpRC = '00000000'x ;
ExpRS = '00000000'x ;

exit_data_length = '00000000'x;
exit_data = '';
GKP_EC_pub_attr_list =,
    '0006'x ||,
    CKA_CLASS || '0004'x || CKO_PUBLIC_KEY ||,
    CKA_KEY_TYPE || '0004'x || CKK_EC ||,
    CKA_TOKEN || '0001'x || CK_TRUE ||,
    CKA_IBM_SECURE || '0001'x || CK_TRUE ||,
    CKA_EC_PARAMS || D2C(LENGTH(secp521r1),2) ||,
    secp521r1 ||,
    CKA_LABEL /* || '1111'x || 'label' */ ;
GKP_EC_prv_attr_list =,
    '0005'x ||,
    CKA_CLASS || '0004'x || CKO_PRIVATE_KEY ||,
    CKA_KEY_TYPE || '0004'x || CKK_EC ||,
    CKA_TOKEN || '0001'x || CK_TRUE ||,
    CKA_IBM_SECURE || '0001'x || CK_TRUE ||,
    CKA_LABEL /* || '1111'x || 'label' */ ;
GKP_Kyber_pub_attr_list =,
    '0006'x ||,
    CKA_CLASS || '0004'x || CKO_PUBLIC_KEY ||,
    CKA_KEY_TYPE || '0004'x || CKK_IBM_KYBER ||,
    CKA_TOKEN || '0001'x || CK_TRUE ||,
    CKA_IBM_SECURE || '0001'x || CK_TRUE ||,
    CKA_IBM_KYBER_MODE || D2C(LENGTH(DER_OID_KYBER_1024_R2),2) ||,
    DER_OID_KYBER_1024_R2 ||,
    CKA_LABEL /* || '1111'x || 'label' */ ;
GKP_Kyber_prv_attr_list =,
    '0005'x ||,
    CKA_CLASS || '0004'x || CKO_PRIVATE_KEY ||,
    CKA_KEY_TYPE || '0004'x || CKK_IBM_KYBER ||,
```

```

        CKA_TOKEN          || '0001'X || CK_TRUE          ||,
        CKA_IBM_SECURE     || '0001'X || CK_TRUE          ||,
        CKA_LABEL          /*|| '1111'X || 'label'         */;
DVK_attr_list_ECDH =,
    '0004'X ||,
    CKA_CLASS              || '0004'X || CKO_SECRET_KEY   ||,
    CKA_IBM_SECURE         || '0001'X || CK_TRUE          ||,
    CKA_KEY_TYPE           || '0004'X || CKK_GENERIC_SECRET ||,
    CKA_VALUE_LEN          || '0004'X || '00000042'X      ;
DVK_attr_list_Kyber =,
    '0004'X ||,
    CKA_CLASS              || '0004'X || CKO_SECRET_KEY   ||,
    CKA_IBM_SECURE         || '0001'X || CK_TRUE          ||,
    CKA_KEY_TYPE           || '0004'X || CKK_AES           ||,
    CKA_VALUE_LEN          || '0004'X || '00000020'X      ;
known_clear_text = COPIES('A',16);

my_token = Left('QSAFE.TEST.TOKEN',44) /* Replace this token handle */

/*****
/* Step 1.1 Generate an ECC key pair for Alice */
*****/
testN = 'ECALICE';
pub_key_attr_list = GKP_EC_pub_attr_list||D2C(LENGTH(testN),2)||testN;
prv_key_attr_list = GKP_EC_prv_attr_list||D2C(LENGTH(testN),2)||testN;
CALL CSFPGKP;
handle_EC_Pub_A = pub_key_object_handle;
handle_EC_Priv_A = prv_key_object_handle;

/*****
/* Step 2.2 Generate an ECC key pair for Bob */
*****/
testN = 'ECBOB';
pub_key_attr_list = GKP_EC_pub_attr_list||D2C(LENGTH(testN),2)||testN;
prv_key_attr_list = GKP_EC_prv_attr_list||D2C(LENGTH(testN),2)||testN;
CALL CSFPGKP;
handle_EC_Pub_B = pub_key_object_handle;
handle_EC_Priv_B = prv_key_object_handle;

/*****
/* Step 2.2 Generate a Kyber key pair for Bob */
*****/
testN = 'QSB0B';
pub_key_attr_list=GKP_Kyber_pub_attr_list||D2C(LENGTH(testN),2)||testN;
prv_key_attr_list=GKP_Kyber_prv_attr_list||D2C(LENGTH(testN),2)||testN;
CALL CSFPGKP;
handle_Kyb_Pub_B = pub_key_object_handle;
handle_Kyb_Priv_B = prv_key_object_handle;

/*****
/* Step 2.3 Derive a key using ECDH(HYBRID_NULL) with Bob's Private */
/* ECC key and Alice Public ECC key */
*****/

```

```

testN = 'DRVGENSECB';
pub_EC_POINT = CSFPGAV(handle_EC_Pub_A,CKA_EC_POINT);
rule_array      = 'EC-DH    ';
attribute_list   = DVK_attr_list_ECDH;
base_key_handle  = handle_EC_Priv_B;
DVK_ParmsList    =,
    CKD_IBM_HYBRID_NULL      ||, /* KDF function code      */
    '00000000'X              ||, /* Optional data length   */
    '0000000000000000'X      ||, /* Optional data address  */
    D2C(LENGTH(pub_EC_POINT),4) ||, /* Public value length    */
    pub_EC_POINT;            /* Public value           */
CALL CSFPDVK;

handle_GenSec_B = target_key_handle;

/*****
/* Step 3.3 Derive a key using ECDH(HYBRID_NULL) with Alice's Private*/
/* ECC key and Bob's Public ECC key                                     */
*****/
testN = 'DRVGENSECA';
pub_EC_POINT = CSFPGAV(handle_EC_Pub_B,CKA_EC_POINT);
rule_array      = 'EC-DH    ';
attribute_list   = DVK_attr_list_ECDH;
base_key_handle  = handle_EC_Priv_A;
DVK_ParmsList    =,
    CKD_IBM_HYBRID_NULL      ||, /* KDF function code      */
    '00000000'X              ||, /* Optional data length   */
    '0000000000000000'X      ||, /* Optional data address  */
    D2C(LENGTH(pub_EC_POINT),4) ||, /* Public value length    */
    pub_EC_POINT;            /* Public value           */
CALL CSFPDVK;
handle_GenSec_A = target_key_handle;

/*****
/* Step 3.4 Derive key using KYBER(HYBRID_SHA256), then encapsulate */
/* Bob's Public Kyber key                                           */
*****/
testN = 'DRVSHARED A';
rule_array      = 'KYBER    ';
attribute_list   = DVK_attr_list_Kyber;
base_key_handle  = handle_Kyb_Pub_B;

DVK_ParmsList    =,
    '00000000'X              ||, /* version                */
    CK_IBM_KEM_ENCAPSULATE    ||, /* mode                    */
    CKD_IBM_HYBRID_SHA256_KDF ||, /* kdf                     */
    CK_FALSE                  ||, /* prepend                 */
    COPIES('00'X,3)           ||, /* reserved                */
    D2C(0,4)                   ||, /* shared data len         */
    D2C(1600,4)                ||, /* cipher len (output)     */
    handle_GenSec_A            ||, /* gen secret key handle   */
    COPIES('42'X,1600);        /* buffer for cipher output */

```



```

CALL CSFPDVK;
CALL parse_Kyber_parmslist;
handle_SharedKey_A = target_key_handle;

/*****
/* Step 4.1 Derive key using KYBER(HYBRID_SHA256) using decapsulate */
/* with Bob's Private Kyber key */
*****/
testN = 'DRVSHARED_B';
rule_array          = 'KYBER    ';
attribute_list      = DVK_attr_list_Kyber;
base_key_handle     = handle_Kyb_Priv_B;
DVK_ParmsList       =,
    '00000000'X      ||, /* version */
    CK_IBM_KEM_DECAPSULATE ||, /* mode */
    CKD_IBM_HYBRID_SHA256_KDF ||, /* kdf */
    CK_FALSE         ||, /* prepend */
    COPIES('00'X,3)  ||, /* reserved */
    D2C(0,4)         ||, /* shared data len */
    d2c( length(cphr),4 ) ||, /* cipher len (input) */
    handle_GenSec_B   ||, /* gen secret key handle */
    cphr              ; /* cipher from previous step */
CALL CSFPDVK;
handle_SharedKey_B = target_key_handle;

/*****
/* Encrypt some data with Alice's SharedKey */
*****/
testN = 'ENCSHAREDA';
rule_array          = 'AES      ECB      ONLY    ';
key_handle          = handle_SharedKey_A;
init_vector         = '';
clear_text          = known_clear_text;
CALL CSFPSKE;
SAY 'ciphertext'||testN||': '||C2X(cipher_text);
cipher_text_SharedKey_A = cipher_text;

/*****
/* Encrypt some data with Bob's SharedKey */
*****/
testN = 'ENCSHAREDB';
rule_array          = 'AES      ECB      ONLY    ';
key_handle          = handle_SharedKey_B;
init_vector         = '';
clear_text          = known_clear_text;
CALL CSFPSKE;
SAY 'ciphertext'||testN||': '||C2X(cipher_text);
cipher_text_SharedKey_B = cipher_text;

/*****
/* Verify cipher text is identical */
*****/

```

```

IF cipher_text_SharedKey_B = cipher_text_SharedKey_A THEN
    SAY 'TESTCASE SUCCESSFUL'

```

```

GETOUT: ;
EXIT;
/*****
/* parse_Kyber_parmslist */
*****/
parse_Kyber_parmslist:
    PARSE VALUE DVK_ParmsList WITH ,
        ver          +4 ,
        mode          +4 ,
        kdf           +4 ,
        pre           +1 ,
        rsvd          +3 ,
        shrdlen        +4 ,
        cphrlen        +4 ,
        gskH           +44 ,
        remaining      ;
    shrdlenD = C2D(shrdlen);
    cphrlenD = C2D(cphrlen);
    PARSE VALUE remaining WITH ,
        shrd          +(shrdlenD) ,
        cphr           +(cphrlenD) ,
        extra          ;
    verP          = ""||C2X(ver)||"X (version "||C2D(ver)||")";
    modeP         = ""||C2X(mode)||"X";
    SELECT;
        WHEN mode = CK_IBM_KEM_ENCAPSULATE THEN
            modeP = modeP||" (CK_IBM_KEM_ENCAPSULATE)";
        WHEN mode = CK_IBM_KEM_DECAPSULATE THEN
            modeP = modeP||" (CK_IBM_KEM_DECAPSULATE)";
        OTHERWISE
            modeP = modeP||" (unknown)";
    END;
    kdfP          = ""||C2X(kdf)||"X";
    SELECT;
        WHEN kdf = CKD_IBM_HYBRID_SHA1_KDF THEN
            kdfP = kdfP||" (CKD_IBM_HYBRID_SHA1_KDF)";
        WHEN kdf = CKD_IBM_HYBRID_SHA224_KDF THEN
            kdfP = kdfP||" (CKD_IBM_HYBRID_SHA224_KDF)";
        WHEN kdf = CKD_IBM_HYBRID_SHA256_KDF THEN
            kdfP = kdfP||" (CKD_IBM_HYBRID_SHA256_KDF)";
        WHEN kdf = CKD_IBM_HYBRID_SHA384_KDF THEN
            kdfP = kdfP||" (CKD_IBM_HYBRID_SHA384_KDF)";
        WHEN kdf = CKD_IBM_HYBRID_SHA512_KDF THEN
            kdfP = kdfP||" (CKD_IBM_HYBRID_SHA512_KDF)";
        OTHERWISE
            kdfP = kdfP||" (unknown)";
    END;
    preP          = ""||C2X(pre)||"X";
    SELECT;
        WHEN pre = CK_FALSE THEN
            preP = preP||" (don't prepend)";

```

```

        WHEN pre = CK_TRUE THEN
            preP = preP||"      (do prepend)";
        OTHERWISE
            preP = preP||"      (unknown)";
    END;
    rsvdP      = ""||C2X(rsvd)||"X";
    shrdlenP   = ""||C2X(shrdlen)||"X ("||shrdlenD||")";
    cphrlenP   = ""||C2X(cphrlen)||"X ("||cphrlenD||")";
    gskHP      = ""||gskH||"";

RETURN;

/* ----- */
/* PKCS #11 Generate Key Pair                               */
/* ----- */
/* Use the PKCS #11 Generate Key Pair callable service to generate */
/* an RSA, DSA, Elliptic Curve, Diffie-Hellman, Dilithium (LI2) or */
/* Kyber key pair.                                             */
/* ----- */
/* See the ICSF Application Programmer's Guide for more details. */
/* ----- */
CSFPGKP:
return_code      = 'FFFFFFFF'X;
reason_code      = 'FFFFFFFF'X;
token_handle     = my_token;
rule_array_count = '00000000'X;
rule_array       = '';
/* pub_key_attr_list is set by caller */
pub_key_attr_list_length = D2C(LENGTH(pub_key_attr_list),4);
pub_key_object_handle    = COPIES(' ',44);
/* prv_key_attr_list is set by caller */
prv_key_attr_list_length = D2C(LENGTH(prv_key_attr_list),4);
prv_key_object_handle    = COPIES(' ',44);
ADDRESS LINKPGM 'CSFPGKP',
            'return_code'          'reason_code'          ,
            'exit_data_length'     'exit_data'            ,
            'token_handle'         ,
            'rule_array_count'     'rule_array'           ,
            'pub_key_attr_list_length' 'pub_key_attr_list' ,
            'pub_key_object_handle' ,
            'prv_key_attr_list_length' 'prv_key_attr_list' ,
            'prv_key_object_handle' ;
IF (return_code \= ExpRC) | (reason_code \= ExpRS) THEN
    DO;
        SAY 'GKP('||testN||')': rc/rs='||C2X(return_code)||'/'||,
                                C2X(reason_code);

        SIGNAL GETOUT;
    END;
Else
    DO;
        SAY 'GKP('||testN||')': successful';
        SAY ' pub_key_object_handle = '||pub_key_object_handle||'';
        SAY ' prv_key_object_handle = '||prv_key_object_handle||'';
    END;

```

```

RETURN;

/* ----- */
/* PKCS #11 Derive Key */
/*
/* Use the PKCS #11 Derive Key callable service to generate a new
/* secret key object from an existing key object.
/*
/* See the ICSF Application Programmer's Guide for more details.
/* ----- */
CSFPDVK:
return_code          = 'FFFFFFFF'X;
reason_code          = 'FFFFFFFF'X;
rule_array_count     = D2C(TRUNC((LENGTH(rule_array)+7)/8),4);
/* rule_array (properly padded) is set by caller */
/* attribute_list is set by caller */
attribute_list_length = D2C(LENGTH(attribute_list),4);
/* base_key_handle is set by caller */
/* DVK_ParmsList is set by caller */
DVK_ParmsList_length = D2C(LENGTH(DVK_ParmsList),4);
target_key_handle     = COPIES('DD'X,44);
ADDRESS LINKPGM 'CSFPDVK',
              'return_code'          'reason_code'          ,
              'exit_data_length'     'exit_data'            ,
              'rule_array_count'     'rule_array'            ,
              'attribute_list_length' 'attribute_list'       ,
              'base_key_handle'       ,
              'DVK_ParmsList_length' 'DVK_ParmsList'         ,
              'target_key_handle'     ;
IF (return_code \= ExprC) | (reason_code \= ExprS) THEN
DO;
  SAY 'DVK('||testN||')': rc/rs='||C2X(return_code)||'/'||,
                                C2X(reason_code);
  SIGNAL GETOUT;
END;
Else
DO;
  SAY 'DVK('||testN||')': successful';
  SAY '  target_key_handle = '||target_key_handle||''';
END;
RETURN;

/* ----- */
/* PKCS #11 Secret Key Encrypt */
/*
/* Use the PKCS #11 Secret Key Encrypt callable service to encipher*
/* data using a symmetric key.
/*
/* See the ICSF Application Programmer's Guide for more details.
/* ----- */
CSFPSKE:
return_code          = '99999999'X;
reason_code          = '99999999'X;
rule_array_count     = D2C(TRUNC((LENGTH(rule_array)+7)/8),4);

```

```

/* rule_array (properly padded) is set by caller */
/* key_handle is set by caller */
init_vector_length      = D2C(LENGTH(init_vector),4);
/* init_vector is set by caller */
chain_data_length       = '00000080'X;
chain_data              = COPIES('00'X,C2D(chain_data_length));
clear_text_length       = D2C(LENGTH(clear_text),4);
/* clear_text is set by caller */
clear_text_id           = '00000000'X;
cipher_text_length      = D2C(C2D(clear_text_length)+16,4);
cipher_text             = COPIES('00'X,C2D(cipher_text_length));
cipher_text_id          = '00000000'X;
ADDRESS LINKPGM 'CSFPSKE'
    'return_code'        'reason_code'      ,
    'exit_data_length'   'exit_data'        ,
    'rule_array_count'   'rule_array'       ,
    'key_handle'         ,
    'init_vector_length' 'init_vector'     ,
    'chain_data_length'  'chain_data'       ,
    'clear_text_length'  'clear_text'       ,
    'clear_text_id'      ,
    'cipher_text_length' 'cipher_text'     ,
    'cipher_text_id'     ;
IF (return_code \= ExprC) | (reason_code \= ExprS) THEN
DO;
    SAY 'SKE('||testN||')': rc/rs='||C2X(return_code)||'/'||,
                                           C2X(reason_code);
    SIGNAL GETOUT;
END;
Else
    SAY 'SKE('||testN||')': successful;
cipher_text = LEFT(cipher_text,C2D(cipher_text_length));
RETURN;

/* ----- */
/* PKCS #11 Get Attribute Value */
/*
/* Use the PKCS #11 Get Attribute Value callable service (CSFPGAV)
/* to retrieve the attributes of an object.
/*
/* See the ICSF Application Programmer's Guide for more details.
/* ----- */
CSFPGAV:
PARSE ARG RATTR.handle,RATTR.attr;
shortHandle = LEFT(RATTR.handle,41);
return_code   = 'FFFFFFFF'X;
reason_code   = 'FFFFFFFF'X;
rule_array_count = '00000000'X;
handle        = RATTR.handle;
rule_array     = '';
attr_list_length = D2C(32000,4);
attr_list      = COPIES('FF'X,32000);
ADDRESS LINKPGM 'CSFPGAV' ,
    'return_code'        'reason_code'      ,
    'exit_data_length'   'exit_data'        ,

```

```

        'handle'
        'rule_array_count' 'rule_array'
        'attr_list_length' 'attr_list'
    IF (return_code \= ExpRC) | (reason_code \= ExpRS) THEN
    DO;
        SAY 'CSFPGAV('||shortHandle||'): rc = '||C2X(return_code)||,
            ' rs = '||C2X(reason_code);
        SIGNAL GETOUT;
    END;
    attr_list = LEFT(attr_list,C2D(attr_list_length));
    number_attributes = C2D(LEFT(attr_list,2));
    attr_list = SUBSTR(attr_list,3);
    DO n = 1 TO number_attributes;
        attr_number = LEFT(attr_list,4);
        attr_list = SUBSTR(attr_list,5);
        attr_val_len = C2D(LEFT(attr_list,2));
        attr_list = SUBSTR(attr_list,3);
        attr_value = LEFT(attr_list,attr_val_len);
        attr_list = SUBSTR(attr_list,attr_val_len+1);
        IF (attr_number = RATTR.attr) THEN
            SIGNAL DONE_W_READ_ATTR;
    END;
    attr_value = 'BADBADBAD';
    DONE_W_READ_ATTR;
    RETURN attr_value;

TCSETUP:

DER_OID_KYBER_1024_R2 = '060B2B0601040102820B050404'X;
secp521r1 = '06052b81040023'x

CKK_IBM_KYBER = '80010024'X;
CKK_EC = '00000003'X
CKK_GENERIC_SECRET = '00000010'X
CKK_AES = '0000001F'X

CKO_PUBLIC_KEY = '00000002'X
CKO_PRIVATE_KEY = '00000003'X
CKO_SECRET_KEY = '00000004'X

CKA_CLASS = '00000000'X
CKA_TOKEN = '00000001'X
CKA_IBM_KYBER_MODE = '8000000E'X
CKA_LABEL = '00000003'X
CKA_IBM_SECURE = '80000006'X
CKA_EC_PARAMS = '00000180'X
CKA_EC_POINT = '00000181'X
CKA_VALUE_LEN = '00000161'X
CKA_KEY_TYPE = '00000100'X

CKD_IBM_HYBRID_NULL = '80000001'X;
CKD_IBM_HYBRID_SHA1_KDF = '80000002'X;
CKD_IBM_HYBRID_SHA224_KDF = '80000003'X;
CKD_IBM_HYBRID_SHA256_KDF = '80000004'X;
CKD_IBM_HYBRID_SHA384_KDF = '80000005'X;

```

```
CKD_IBM_HYBRID_SHA512_KDF = '80000006'X;

CK_IBM_KEM_ENCAPSULATE    = '00000001'X;
CK_IBM_KEM_DECAPSULATE    = '00000002'X;

CK_TRUE                    = '01'x
CK_FALSE                   = '00'x
return

NOVALUE:
SAY "Condition NOVALUE was raised."
SAY CONDITION("D") "variable was not initialized."
SAY sigl||': '||SOURCELINE(sigl)
EXIT;
```



Generating a one-way hash

The examples in this appendix are REXX executables that can be used to generate an SHA-512 one-way hash, using CCA and PKCS#11.

This appendix includes the following topics:

- ▶ F.1, “CCA SHA-512 one-way hash REXX sample” on page 188
- ▶ F.2, “PKCS #11 SHA-512 one-way hash REXX sample” on page 189

F.1 CCA SHA-512 one-way hash REXX sample

A CCA SHA-512 one-way hash REXX sample is shown in Example F-1.

Example F-1 CCA SHA-512 one-way hash REXX sample

```
/* REXX */

/*-----*/
/* Generate SHA-512 hash using CCA One-Way Hash service */
/*-----*/

/* expected results */
ExpRc = '00000000'x
ExpRs = '00000000'x

BOWH_Rule_Array = 'SHA-512 ' || 'ONLY' ;
BOWH_Text       = '0123456789ABCDEF';
BOWH_Hash       = copies('00'x, 64);
BOWH_Chain_Vector = copies('00'x,128);

call CSNBOWH

say 'BOWH Hash: ' c2x(BOWH_Hash)

Exit

/* ----- */
/* One-Way Hash Generate */
/*
/* Used to generate a one-way hash
/*
/* See the ICSF Application Programmer's Guide for more details.
/* ----- */

CSNBOWH:

/* initialize parameter list */
BOWH_rc      = 'FFFFFFFF'x ;
BOWH_rs      = 'FFFFFFFF'x ;
BOWH_Exit_Length = '00000000'x ;
BOWH_Exit_Data  = '00000000'x ;
BOWH_Rule_Count = d2c(length(BOWH_Rule_Array)/8,4);
BOWH_Text_Length = d2c(length(BOWH_Text),4);
BOWH_Chain_Vector_Length = d2c(length(BOWH_Chain_Vector),4);
BOWH_Hash_Length = d2c(length(BOWH_Hash),4);

/* call CSNBOWH */
address linkpgm 'CSNBOWH' ,
               'BOWH_rc'      'BOWH_rs'      ,
               'BOWH_Exit_Data_Length' 'BOWH_Exit_Data' ,
               'BOWH_Rule_Count'  'BOWH_Rule_Array' ,
               'BOWH_Text_Length' 'BOWH_Text'      ,
               'BOWH_Chain_Vector_Length' 'BOWH_Chain_Vector' ,
               'BOWH_Hash_Length'  'BOWH_Hash'      ;
```

```

if (BOWH_rc \= ExpRc | BOWH_rs \= ExpRs) then
  say 'BOWH failed: rc =' c2x(BOWH_rc) 'rs =' c2x(BOWH_rs) ;
else
  say 'BOWH successful: rc =' c2x(BOWH_rc) 'rs =' c2x(BOWH_rs) ;

return

```

F.2 PKCS #11 SHA-512 one-way hash REXX sample

A PKCS #11 SHA-512 one-way hash REXX sample is shown in Example F-2.

Example F-2 PKCS #11 SHA-512 one-way hash REXX sample

```

/* REXX */

/*-----*/
/* Generate SHA-512 hash using PKCS #11 One-Way Hash service */
/*-----*/

/* expected results */
ExpRc = '00000000'x
ExpRs = '00000000'x

/* Call PKCS#11 One-Way Hash with generated token */
POWH_Rule_Array = 'SHA-512 ' || 'ONLY ' ;
POWH_Text      = '0123456789ABCDEF';
POWH_Hash      = copies('00'x, 64);
POWH_Chain_Vector = copies('00'x,128);
POWH_Handle    = Left('QSAFE.TEST.TOKEN',44)

call CSNPOWH

say 'POWH Hash: ' c2x(POWH_Hash)

Exit
/* ----- */
/* PKCS #11 One-Way Hash, Sign, or Verify */
/* */
/* Use the PKCS #11 One-Way Hash, Sign, or Verify callable service */
/* to generate a one-way hash on specified text, sign specified */
/* text, or verify a signature on specified text. */
/* */
/* See the ICSF Application Programmer's Guide for more details. */
/* ----- */

CSNPOWH:

/* initialize parameter list */
POWH_RC      = 'FFFFFFFF'x ;
POWH_RS      = 'FFFFFFFF'x ;

```

```

POWH_Exit_Length      = '00000000'x ;
POWH_Exit_Data        = '' ;
POWH_Rule_Count       = d2c(length(POWH_Rule_Array)/8,4);
POWH_Text_Length      = d2c(length(POWH_Text),4);
POWH_Text_id          = '00000000'x ;
POWH_Chain_Vector_Length = d2c(length(POWH_Chain_Vector),4);
POWH_Hash_Length      = D2C(Length(POWH_Hash),4);

/* call CSNPOWH */
address linkpgm 'CSFPOWH' ,
               'POWH_RC'          'POWH_RS'          ,
               'POWH_Exit_Length' 'POWH_Exit_Data'    ,
               'POWH_Rule_Count'   'POWH_Rule_Array'   ,
               'POWH_Text_Length'  'POWH_Text'        ,
               'POWH_Text_id'      ,
               'POWH_Chain_Vector_Length' 'POWH_Chain_Vector' ,
               'POWH_Handle'        ,
               'POWH_Hash_Length'   'POWH_Hash'        ;

if (POWH_rc \= ExpRc | POWH_rs \= ExpRs) then
  say 'POWH failed: rc =' c2x(POWH_rc) 'rs =' c2x(POWH_rs) ;
else
  say 'POWH successful: rc =' c2x(POWH_rc) 'rs =' c2x(POWH_rs) ;

return

```



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